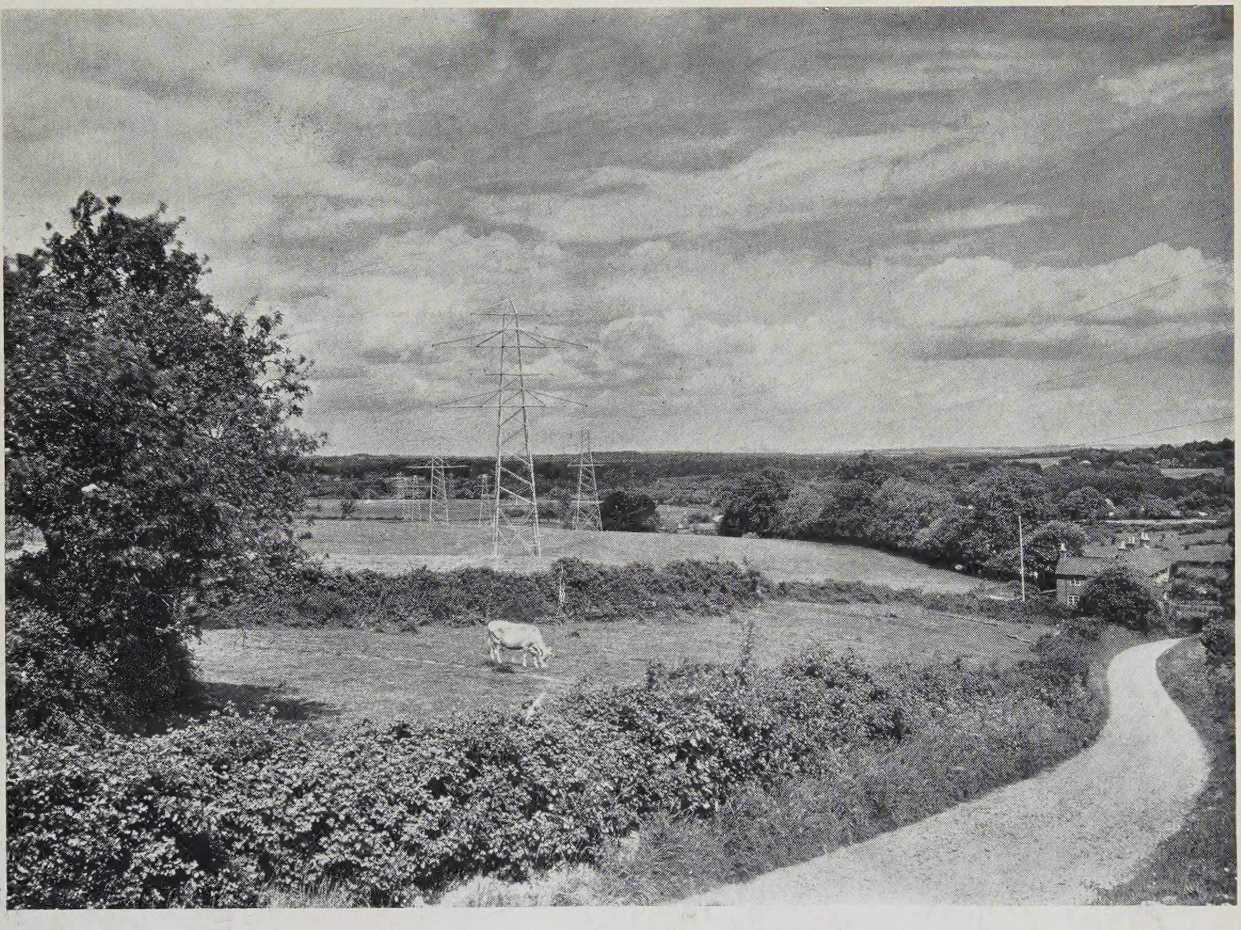
Electrical Engineering

October
1934



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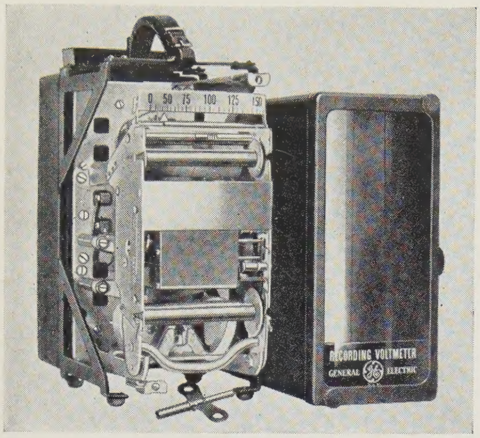

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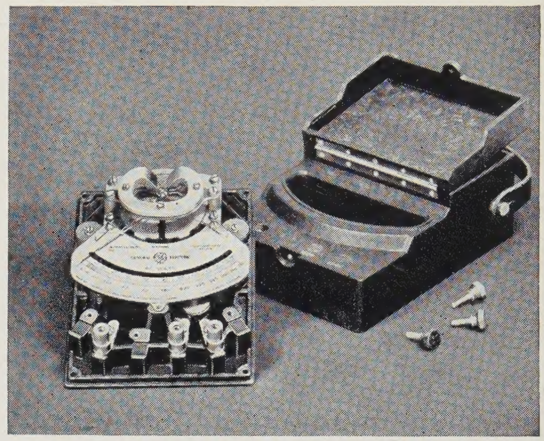

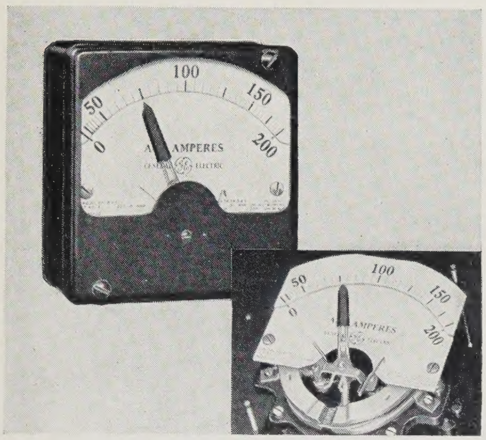

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Front Cover

Transmission towers in England, showing secondary transmission (33,000-volt) lines in Hampshire supplying electricity from Nursling to Salisbury in southwest England

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Special Feature

A.I.E.E. Papers

News of Institute and Related Activities 1423

—Turn to Next Page

CORRECTION: In the news report of the 1934 A.I.E.E. summer convention held June 25–29 at Hot Springs, Va., which was published on p. 1225–9 of the August issue, White Sulphur Springs, W. Va., was incorrectly stated to be in District No. 4; it is in District No. 2.

Another Message From the President

To the Institute Membership—

IN MY last message I spoke of the desirability of "tidying up" the Institute and the profession and mentioned a number of proposals which seemed to be directed toward that result. Now the cardinal principle of tidiness is "a place for everything and *everything in its place*," and since writing that message I have been thinking about that principle in relation to the A.I.E.E.

In many old New England homes there used to be a piece of furniture called a "what-not." It stood in a corner of the living room and was a depository for all sorts of miscellaneous objects. Somehow, as I look over the names of Institute members listed as "Associates," I cannot help remembering my grandmother's old what-not, and wondering if tidiness like charity, should not begin at home. Would it not be very much in order, as a first step toward tidying up the Institute, for each member to consider his own position therein and, if necessary, take action to put himself in his proper "place."

Specifically, it seems to me very untidy indeed to have a compartment labelled "Associates" all cluttered up, as it is, with people who ought to be in compartments labelled "Juniors," "Members," and "Fellows." In fact, this condition seems to me not only untidy but unfair both to the individuals concerned and to everybody else. It places every Associate in a false position because no one can tell who is which.

Undoubtedly our constitutional organization is partly responsible for this untidy condition. We never have had in the Institute a specific place for the younger engineers in the apprenticeship stage of their development. We have dumped them into the Associate "what-not" where they have found themselves in the company of a heterogeneous throng ranging all the way from novices like themselves to engineers of world-wide reputation. With the Associate grade thus overlapping and blanketing all the others the significance of the successive professional grades of Member and Fellow has been shrouded and largely nullified. The designated pathway of progress in professional standing has been hidden amid this confusion, hence there has been little incentive for orderly advancement from grade to grade and the confusion in the Associate grade has become self-perpetuating and cumulative.

Is it not time to clean house? A "Junior" grade of membership would help, but without waiting for the constitutional changes necessary to add this needed "reception room" to our edifice we can at least put our existing house in order if each of us will find and enter the "compartment" where he belongs. It seems to me we owe this much to our own professional standing as well as to the dignity and prestige of the Institute and the engineering profession. I think we should not forget that to "maintain a high professional standing among its members" is 1 of the 2 constitutional objects of the Institute.

If you have thoughtlessly allowed yourself to drift into the false and anomalous position above described, especially if you are a responsible engineer to whom younger men look for inspiration and guidance, I earnestly commend the above thoughts to your consideration and appropriate action. Let's start tidying up the profession by putting our own house in order.

Faithfully yours,

J. Allen Johnson

President A.I.E.E.

P.S. Transfer application blanks can be obtained from the national secretary or from your Section committee on transfers.

Operational Calculus

By MURRAY F. GARDNER, Member A.I.E.E.
Massachusetts Institute of Technology, Cambridge

Operational calculus is useful in both the formulation and solution of the differential equations involved in engineering problems, and because of its power and directness it is finding increasing favor in engineering analysis. It is especially helpful to the electrical engineer because many of his problems involve transients, the analysis of which requires the solution of differential equations. In this article is presented not a popular treatment of operational calculus (several of which already have been published), but rather a brief survey of the historical development, an introduction to the background, and a summary of the threads of rigorous analysis that bind the many processes into a rational and systematic whole. This is the tenth in a series of special articles developed under the sponsorship of the A.I.E.E. committee on education.

WHILE, in general, transients in physical systems represent undesirable disturbances which must be allowed for with suitable factors of safety in engineering design and operation, today they are being intentionally produced and usefully applied in numerous fields. For examples where they appear in the latter aspect, consider the sweep circuit for the cathode ray oscillograph beam, the high voltage or high current surge generators, and the inverter with its operation a continuous series of transients. The analysis of transients, in whichever aspect they may appear, constitutes a problem of growing practical importance in progressive engineering. In the encouraging progress being made in this field operational calculus is playing a steadily increasing part.

Transient analysis involves the solution of differential equations. In his formal training the engineer has studied ordinary differential equations, particularly the linear type with constant coefficients, and often simple partial differential equations. Operational calculus can helpfully supplement this training. It can help both in the formulation and in the solution of the differential equations of engineering problems. Through the aid to thinking given by the directness of its notation and the powerfulness of its concepts, expression in mathematical language of the physical relations more readily is effected; through its systematic procedure and well-organized summaries of previous experience, solution more easily is accomplished.

Popular treatments of operational calculus are available in technical literature, so this article aims to do something different. It presents a brief survey of the historical development, an introduction to the background, and a summary of the threads of rigorous analysis that bind the many processes into a rational and systematic whole. Any discussion of these aspects must involve functional reasoning in somewhat unfamiliar terms. From this, however, it is not to be gathered that operational calculus is composed of an assortment of bizarre mathematics. On the contrary it embodies an exceedingly compact symbolic substitute for much difficult mathematics. One can appreciate this only from some acquaintance with the mathematics for which it serves, from which it derives its limitations, and from which it gathers guidance in its further development. These aspects, rather than the technique of its application, are the ones discussed here.

Operational calculus applies to systems or situations where cause and effect stand in linear relation. Since in general for practical engineering purposes only first-order effects need be considered, a great range of physical systems can be treated as linear, and their differential relationships lead to equations within the scope of operational methods.

As operational calculus still is evolving, it should not be characterized too closely; but, in general, in its application to differential equations it embodies features such as outlined here. To be explicit, time will be considered the independent variable. The time differentiators in the differential equations are replaced by a simple symbol (the use of p for $\frac{d}{dt}$ is almost universal). The resulting supplementary equations are treated as equations in algebra, and solved algebraically. The disturbing forces may be of general form, but the most common ones are the unit constant force $\mathbf{1}$, the unit exponential $\epsilon^{at}\mathbf{1}$, and the unit sinusoid $\sin \omega t\mathbf{1}$. The symbol $\mathbf{1}$ represents a time function which is zero for $t<0$, and unity for $t>0$. Its product with any other time function is likewise zero for $t<0$. The initial conditions of the physical system are generally those of rest, or of equilibrium; if not, these conditions are included in the supplementary equations, each being responsible for certain added terms.

Taking for example a case expressible by a system of ordinary differential equations in which there is a single unit disturbing force $\mathbf{1}$, and the initial conditions are those of rest, the algebraic solution of the supplementary equations for the unknown $h(t)$ is

$$h(t) = \frac{1}{H(p)}\mathbf{1} \tag{1}$$

where $\frac{1}{H(p)}$ is the operator, and $\mathbf{1}$ the operand. The operator embodies all pertinent information about the physical system, such as its interconnections, parameters, and initial conditions. The operand, however, while termed the disturbing "force," need

not have the dimensions of a force. For instance, it may be a suddenly applied electromotive force, current, charge, torque, velocity, displacement, temperature, rate of heat flow, or other independently variable quantity. The requirement is that its entire history and future variation be known, and appear in functional form in this part of the equation. For the simple case considered here, its past was zero; its present and future are unity. Solving eq 1 consists in applying any of them any possible processes for converting the right member into functions of time and the system parameters. A survey of these processes constitutes a large part of the study of operational calculus, and cannot be reproduced here.

A distinctive feature of operational calculus, when used in this manner to solve differential equations, is that it gives directly as its result the *complete* solution of the problem set, with all initial and boundary conditions satisfied. Also, unless it is a convergent series solution, the steady-state and transient portions (i. e., the particular integral and the complementary function with all its constants of integration evaluated) are readily distinguishable. The patchwork process of the ordinary calculus in which a general solution, consisting of particular integral and complementary function, is obtained first and revised afterward to suit the initial conditions, is replaced by a symbolic process involving complete mathematical expression of the problem at the outset, and a systematic conversion of resulting operator and operand into functions of the independent variable and system parameters. Because of this surprising power and directness, operational calculus is finding increasing favor in engineering analysis.

Fields in which the electrical engineer finds use for operational calculus are many and varied, and only a few can be enumerated. It finds application in the analysis of:

1. Traveling wave transients on transmission lines and cables, including reflections at junction points and terminal apparatus.
2. Surge protection of transformers and rotating machinery.
3. Short-circuit transients in a-c machines.
4. Transient voltage regulation of d-c generators.
5. Circuits of high voltage and high current surge generators.
6. Transients in relay and control circuits.
7. Propagation of communication signals.
8. Transients in filter circuits and artificial lines.
9. Transient interference between a grounded transmission line under fault conditions and an adjacent communication line.
10. Cathode ray oscillograph potential-divider, time-delay, and sweep circuits.
11. Transients in vacuum tube amplifier and oscillator circuits.
12. Transients in measurement circuits.
13. Field transients in iron cores partially laminated and partially solid, influencing design of field circuits for quick-response excitation of large a-c generators, and for rapid-reversing d-c rolling-mill motors.
14. Transient heat flow in machinery, cables, and rectifier seals.
15. Transient sound propagation.
16. Transient mechanical vibrations.

Historical Development

Operational methods of solving linear differential equations as met in formal courses in differential equations are largely from the work of Boole (1865) a mathematician of Queen's University, Ireland. He treated the differentiator $\frac{d}{dx}$ as an operator D, showed that the latter obeyed the fundamental laws of algebra as though it were a symbol of quantity rather than operation, and gave theorems for its use in solving both ordinary and partial differential equations. In particular, he was responsible for the partial-fraction expansion scheme of solving the constant-coefficient type of linear equations.

The operational calculus considered here, however, has reference more particularly to the operator processes of Heaviside, who, while not the originator of the symbolic method of treating differential equations, did devise for it those remarkable features of directness and power that make it appeal so strongly to one with a practical interest in mathematics. Operational symbolism first appeared in Heaviside's papers in 1881. Not until 5 years later did he begin to improve upon conventional procedure in the evaluation of integration constants—still a burdensome after-adjustment even with the operational processes of Boole.

In 1886 Heaviside employed his "conjugate" theorem as an aid in evaluating the coefficients of normal function solutions of distributed-system transients. Vallarta (1926) has pointed out that this undoubtedly marked the beginning of Heaviside's normal function expansion theorem. In a paper published a month later in 1886, Heaviside presented this expansion theorem in completed form—casually, in a footnote. The basis here was not his conjugate theorem, but an algebraic expansion in partial fractions such as Boole had employed. As a result of this advance, integration constants became expressible directly by formula provided the initial conditions were those of rest and the disturbing cause a simple unit force.

Within the next 3 years, Heaviside had introduced in his papers the majority of the features associated with his operational methods, such as "resistance" and "conductance" operators for formulation of operational solutions, irrational operators, the unit function, expansions in normal functions, expansions in series, expansions in waves, the transfer operator, and the shifting operation. These features appear in Volume II of his "Electrical Papers" (1892). In Volume II (1899) of his "Electromagnetic Theory" he enlarges greatly upon these processes in connection with the solution of the transient behavior of cables, lines, and networks. In Volume III (1912) is a section devoted to the solution of definite integrals by differential transformation, which will be of interest later in this article. These and his papers "On Operators in Physical Mathematics" in 1893 and 1894 constitute the principal sources of information on his contributions. Nowhere in these, however, does he give any real systematic discussion of his operational processes, correlating them, and establishing their relationship to more formal mathematics. His use of novel methods without introduction, and with small explanation, was bewildering indeed. He was pioneering in the difficult field of diffusion and wave propagation; new mathematical procedures seemed necessary, and he did not hesitate to devise them. It was typical of him with his ec-

centric ways that he should verify carefully all that he did, but leave proof and justification of his processes to others. As a consequence of an unsystematic presentation of his methods, and their difficult and sometimes unorthodox nature, some 30 years elapsed before they received anything like formal substantiation.

Bromwich, a Cambridge mathematician, appears to have been the first to supply formal justification of Heaviside's methods. A paper he presented in 1914, but which was not published until 1916, interpreted these methods in terms of complex function theory. Unit function was expressed as a line integral in the complex plane, and the interpretation of the operational equation (eq 1) was given as

$$h(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{\epsilon^{ut}}{uH(u)}\,du \tag{2}$$

Interpretation of this will appear later.

Wagner in Germany apparently was working simultaneously along lines similar to those followed by Bromwich, seeking to correlate Heaviside's processes with function theory, for he published in 1916 a justification likewise employing line integration in the complex plane. He gave as his interpretation of eq 1 the complex line integral

$$h(t) = \frac{1}{2\pi j}\int_L \frac{\epsilon^{ut}}{uH(u)}\,du \tag{3}$$

where L designates the path of integration in the complex plane. The difference in these 2 line integrals rests solely in the path of integration chosen.

Carson, working along independent lines in 1925 evolved an entirely different interpretation of Heaviside's processes. He expressed the relation between $h(t)$ and $\frac{1}{H(p)}$ of eq 1 as an equation of the form

$$\frac{1}{uH(u)} = \int_0^\infty h(t)\epsilon^{-ut}\,dt \tag{4}$$

where u may be complex, but its real part must be positive. With $h(t)$ the unknown, eq 4 is an integral equation. It gives $h(t)$ implicitly. Limited to this relationship alone, the determination of $h(t)$ to satisfy the equation would be exceedingly difficult in general were it not for the fact that integrals of this form have been much studied and their evaluations tabulated in complete tables of integrals. However, Carson did not stress it so much as a means of evaluating operational equations as of providing guidance to rules of operational transformations, and substantiation of results obtained operationally.

Like previous writers, Carson considered the solution resulting from unit function with initial rest conditions the fundamental one; but for more general disturbing forces he utilized the Boltzmann-Hopkinson superposition theorem. Thus the solution of the general operational equation

$$h(t) = \frac{1}{H(p)} f(t)\,\mathbf{1} \tag{5}$$

proceeded in 2 steps: first

$$h_1(t) = \frac{1}{H(p)}\,\mathbf{1} \tag{6}$$

with interpretation guided by eq 4, then by the superposition theorem

$$h(t) = \frac{d}{dt}\int_0^t h_1(\lambda)f(t-\lambda)d\lambda \tag{7}$$

Interpretations of Heaviside's processes by complex line integral and by integral equation were naturally not without relation, for each expressed a connection between the operator $\frac{1}{H(p)}$ and its equivalent $h(t)$. They were joined when Lévy (1926) and March (1927) pointed out that they constitute the complementary parts of a generalized Fourier integral. That is, if $h(t)$ is the unknown, eq 4 is an integral equation, and eq 2 is its solution; however, if $\frac{1}{H(p)}$ is the unknown, the rôles of the equations are interchanged.

One unskilled in formal mathematics finds Bromwich's papers difficult reading. It is fortunate therefore that Jeffreys (1927), also of Cambridge, has supplied an interpretation; but in his tract on operational methods he has done more than just this. Starting with an operational method, introduced by Caqué (1864), for solving an ordinary linear first-order differential equation (by repeated substitutions resulting in a series for interpretation by repeated integrations), Jeffreys builds up a complete treatment of simultaneous ordinary linear differential equations with constant coefficients. Whereas this supplementary approach could be used for ordinary differential equations, for partial differential equations substantiation still had to rest entirely upon the line integral treatment.

Jeffreys includes in his development a scheme for handling operationally initial conditions other than those of rest. Of course, the systems subject to analysis by operational methods must be linear, and a linear system having such arbitrary initial conditions can be brought within the scope of the conventional operational method by artifices; but at best these are usually awkward to handle, and a straightforward operational formulation of the entire problem at the outset is much to be preferred.

Campbell and Foster published in 1931 a table of Fourier transforms, based upon an earlier paper of Cambell's (1928), which makes available in convenient form to the engineer those solutions of the Fourier integral that the professional mathematician has made. By alliance of the operational calculus with the Fourier integral, this table of transforms can be interpreted conveniently as one of operational formulas, and, as such, is the most complete table of the latter available.

In 1929 van der Pol began a series of papers that has influenced materially recent developments in the operational method. The basis of his treatment is the same integral equation used by Carson, but written

$$\frac{1}{H(u)} = u\int_0^\infty h(t)\epsilon^{-ut}\,dt \tag{8}$$

and is the definition of his symbolic relation

$$\frac{1}{H(u)} \doteq h(t) \tag{9}$$

in which the unit function is not used. His method is one of transforms. The differential equation is replaced by a supplementary equation as before, but its terms are the transforms, term for term, of the original equation—a new approach entirely in operational calculus. With previous methods, the supplementary equation has been expressed in operational notation, there has been an idea of operator and operand, and the rules for interpreting its solution have been derived from study of either a complex line integral or an integral equation, each involving a complex variable. In this newer method, the supplementary equation is expressed directly in functions of a complex variable. The concept of operator and operand is discarded. Its unknowns are the transforms of the unknowns in the original equation. The problem becomes one of solving the supplementary equation to determine the actual form of the desired transform, and then converting this by retransformation or by operational methods into its equivalent original. Because van der Pol uses $\frac{1}{H(u)}$ as symbolically equivalent to $h(t)$ (rather than using $\frac{1}{uH(u)}$ which would be its actual Laplace transform), and because he uses p as the symbol for his complex variable, his supplementary equations for linear differential equations with constant coefficients appear similar to those found with the older method; but their true significance is different.

This has proved a fruitful process. By means of it van der Pol has been able to do all that was done formerly, including the treatment directly of arbitary initial values. In addition he has extended the operational method to the solution of linear differential equations with variable coefficients; and, amplifying Heaviside's methods of solving definite integrals by differential transformations, he has developed a system of simultaneous operational calculus, and a symbolic treatment of definite integrals.

Some recent work of Lowan (1934) is related to operational developments. Using the processes of van der Pol he has shown the use of the transform in the solution of certain partial differential equations having arbitrary initial and boundary conditions to be satisfied. He has used the actual Laplace transform, rather than its modified form employed by van der Pol. As with the latter's work, when solution of the supplementary equation has been secured it can be retransformed, or else treated operationally, to gain the solution of the original problem. The displacement of operational processes by the transformation scheme is here almost complete.

Many others have contributed to the gradual substantiation, development, and promotion of operational calculus, and it is regrettable that this brief survey cannot include some mention of the work of Berg, Bush, Fry, Georgi, Pennell, Pleijel, Stachó, Sumpner, Volterra, Wiener, and others.

Fourier Integral Background

The most satisfactory substantiations of Heaviside's work are based upon one aspect or another of the Fourier integral. Against the background supplied by this, his methods become well understood as the shorthand expressions for rigorous mathematical relationships. There has been a distinct gain in power for the operational calculus from this association. The Fourier integral is an old and highly developed tool for the treatment of transient phenomena. The parallel between its transform theory and operational processes has been well utilized, and, in recent developments there is evidence of a trend in operational calculus away from rather constraining concepts of "operator" and "operand" toward the more flexible and more powerful processes of the transform.

One familiar with only the conventional features of the operational calculus and unacquainted with the associated Fourier integral background would find the recent developments a rather bewildering interchange of functions and operators in equations, integrals, and summations. There are in use such expressions of relationship as

$\frac{1}{H(u)}$ "is symbolically equivalent to" $h(t)$

$\frac{1}{H(u)}$ is the "image," and $h(t)$ is its "original"

$\frac{1}{uH(u)}$ "is the transform of" $h(t)$

$\frac{1}{uH(u)}$ "is the mate of" $h(t)$

$\frac{1}{uH(u)}$ is the "convert," and $h(t)$ is its "revert"

The unit function seldom is expressed. Heaviside himself did not always express an operand, but his unit function was implied. He departed furthest from this in his treatment of definite integrals by differential transformation, where he replaced functions with operator equivalents, and conversely, quite independent of functional arrangement. It was distinctly a transform process. It is this aspect of Heaviside's work that van der Pol and his co-authors have revived and extended in their "simultaneous operational" and "symbolic" calculus. They have found the operator-operand concepts difficult to reconcile with this freedom of manipulation, and accordingly have frankly discarded them in favor of the transform concept.

Because of this trend in operational calculus toward the use of transforms rather than operators, and because of the many rules for manipulation and interpretation of transforms, and the large collection of transform pairs available as a result of the mathematicians study of the Fourier integral, it is most desirable for one utilizing operational calculus to have some acquaintance with the Fourier method of dealing with transients. The rules for its transforms will guide him in the interpretation and use of his operational processes, and its transform pairs will provide him with a host of operational formulas.

As the engineer is well acquainted with the Fourier series, it will be taken as the introduction to its more powerful ally, the Fourier integral. The form of the integral can be determined quickly from the series by rather nonrigorous steps. This, however, will not be shown here, but rather the correspondence

between their expressions. The argument will be clothed with a certain amount of familiar electrical engineering terminology.

Consider a linear, stable, dissipative, nonimpulsive, 2-terminal network available for which the input impedance $Z(j\omega)$ is known as a function of frequency f, with $\omega = 2\pi f$. If a periodic but nonharmonic emf be applied to this network, it is known from experience that the resulting steady state input current likewise will be periodic and nonharmonic, and in general of wave form different from that of the emf. The computation of this case involves the use of the Fourier series. The emf, presumed to be physically realizable and satisfying all the requirements for Fourier analysis, can be expressed as a summation of sinusoidal emf's of fundamental and harmonic frequencies. The network being linear, the principle of superposition applies. The current resulting from each emf component can be computed separately, and these component currents superposed in proper phase relation to determine the total resulting steady state current. In brief, the process consists of 3 steps: (1) analysis of the emf to determine its components, (2) solution for steady state current component corresponding to each, and (3) synthesis of these components to obtain the total steady state current.

The Fourier series commonly is expressed in trigonometric functions, but a more compact and convenient expression can be made with their equivalent exponential oscillating functions. The period of the fundamental is taken as $2S$. Then, except at any points of discontinuity,

$$e(t) = \frac{1}{2}\sum_{n=-\infty}^{\infty} E\left(jn\frac{\pi}{s}\right)\epsilon^{jn\frac{\pi}{s}t} \tag{10}$$

where

$$E\left(jn\frac{\pi}{s}\right) = \frac{1}{s}\int_{-s}^{s} e(\lambda)\,\epsilon^{-jn\frac{\pi}{s}\lambda}\,d\lambda. \tag{11}$$

Equation 11 constitutes the analysis of $e(t)$, and 10 a synthesis to regain $e(t)$. The n^{th} component of current associated with the n^{th} component of emf is

$$\frac{E\left(jn\frac{\pi}{s}\right)}{Z\left(jn\frac{\pi}{s}\right)}\epsilon^{jn\frac{\pi}{s}t}$$

and the total steady state current is

$$i(t) = \frac{1}{2}\sum_{n=-\infty}^{\infty}\frac{E\left(jn\frac{\pi}{s}\right)}{Z\left(jn\frac{\pi}{s}\right)}\epsilon^{jn\frac{\pi}{s}} \tag{12}$$

Equation 12 constitutes the synthesis to obtain $i(t)$. It is to be emphasized that this has dealt only with the steady state, and that both emf and current are periodic.

The sudden application at $t = 0$ of an emf to the network will produce, in general, not only the steady state current, but also a certain amount of transient distortion, finally disappearing since the circuit is dissipative. To express this entire result requires the Fourier integral.

Whereas before, it was sufficient to consider only one complete cycle of emf and current, it is necessary now to express their entire history. For this case an emf will be considered that is zero for $t<0$, nonperiodic for $t>0$ but never becomes infinite, and damps out at least exponentially for t very great. Such an emf has an infinite period. The Fourier integral, by which it can be expressed, appears like a limiting form of the series in which $2S$ has been allowed to increase indefinitely, and $\frac{n\pi}{S}$ has become the general radian frequency ω. It is

$$e(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E(j\omega)\epsilon^{j\omega t}\,d\omega \tag{13}$$

where

$$E(j\omega) = \int_{-\infty}^{\infty} e(\lambda)\epsilon^{-j\omega\lambda}\,d\lambda \tag{14}$$

and again there are reservations about points where $e(t)$ is discontinuous. Equation 14 constitutes the analysis of $e(t)$, and 13 a synthesis to regain $e(t)$. These 2 expressions can be combined by substitution to form the double Fourier integral

$$e(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\epsilon^{j\omega t}\int_{-\infty}^{\infty} e(\lambda)\epsilon^{-j\omega\lambda}\,d\lambda\,d\omega \tag{15}$$

integration with respect to λ being carried out first.

The component of current associated with the differential component of emf of radian frequency ω is

$$\frac{E(j\omega)\,d\omega}{Z(j\omega)}\epsilon^{j\omega t}$$

The expression for the input current resulting from the application of the emf to the above network, initially without currents or charges, is the Fourier integral

$$i(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{E(j\omega)}{Z(j\omega)}\epsilon^{j\omega t}\,d\omega \tag{16}$$

Equation 16 constitutes the synthesis to obtain $i(t)$. It is the *total* current at any time t. While evidently from physical reasoning $i(t)$ must be zero for $t<0$, and must vanish for large positive values of t, yet it is expressed as an infinite sum of differentially small, oscillating, *undamped* currents. The emf is not applied until $t = 0$, and there is actually no current in the circuit until this instant. The integral states these facts in a surprising way. According to it, the emf components all were applied to the network in the remote past, and have been actively energizing it ever since. Each of the component currents corresponding to them may have had transient distortion in the beginning, but at least it disappeared in the great past leaving only a system of oscillating undamped components to come down through time. Until time $t = 0$ is reached, these components have had the proper amplitude and phase exactly to annul one another. Beyond this point, without the slightest change in amplitude or phase, they give as their sum the actual current existent in the circuit. One may protest against the artificiality of this concept, but must concede its great power in reducing all transient phenomena to terms of the steady state—which is so well understood, and easily calculated.

Replacing $e(t)$ by $g(t)$ and $E(j\omega)$ by $F\left(\frac{\omega}{2\pi}\right)$ in eqs 13 and 14, and putting $\omega = 2\pi f$, there is obtained

$$g(t) = \int_{-\infty}^{\infty} F(f)\epsilon^{j2\pi ft}\,df \tag{17}$$

where

$$F(f) = \int_{-\infty}^{\infty} g(\lambda)\epsilon^{-j2\pi f\lambda}d\lambda \tag{18}$$

These are the symmetrical forms of the Fourier integral used in the Campbell and Foster table of "Fourier Integrals for Practical Applications." The expression $F(f)$ is the Fourier transform of $g(t)$, and conversely. As with eqs 13 and 14, these integrals are limited to functions $g(t)$ which vanish, at least exponentially, as t approaches either $\pm\infty$.

Among the disturbing forces most commonly used are constant d-c emf's and constant a-c emf's applied at $t = 0$. Since neither of these is representable by the Fourier integral just given, because of their failure to subside to zero as t increases, a more general form of the Fourier integral is required. Thus, if $e(t)$ never becomes infinite, is zero for $t<0$, and meets all other requirements for the Fourier integral except that $\int_{-\infty}^{\infty} |e(t)|dt$ is not finite, it is possible to form the double integral (eq 15) for $\epsilon^{-ct}e(t)$, where c is a positive real constant, since this product function is within the requirements. When the substitution $u = c + j\omega$ is made, and the lower limit for the integration with respect to λ is taken as 0, since $e(-\lambda) = 0$, there is obtained

$$e(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \epsilon^{ut}\int_{0}^{\infty} e(\lambda)\epsilon^{-u\lambda}d\lambda\, du \tag{19}$$

This likewise can be written in 2 parts, so as to disclose clearly the steps of analysis and synthesis

$$e(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} E(u)\epsilon^{ut}\,du \tag{20}$$

where

$$E(u) = \int_{0}^{\infty} e(\lambda)\epsilon^{-u\lambda}\,d\lambda \qquad Re\ u = c > 0 \tag{21}$$

This is a generalized form of the Fourier integral. The function $E(u)$ of the complex variable u is called the Laplace transform of $e(t)$; it is a generalized type of Fourier transform. This integral and transform have been much used in recent developments of operational calculus.

The standard disturbing force in operational calculus is the unit function. It is zero for $t<0$, and unity for $t>0$—the simplest kind of discontinuous time function, consisting of a unit step at the origin.

In terms of emf's, the unit function represents an ideal battery of unvarying unit voltage connected to the circuit at $t = 0$. It requires, however, the generalized integral (eq 20) for its expression. Thus

$$1 = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{\epsilon^{ut}}{u}\,du \tag{22}$$

since by eq 21

$$\frac{1}{u} = \int_{0}^{\infty} 1\epsilon^{-u\lambda}\,d\lambda \qquad Re\ u > 0 \tag{23}$$

Equation 22 expresses unit function as an infinite sum of differentially small complex exponentials of the form $\frac{du}{u}\epsilon^{ut}$. Each of these exponential components of emf produces a differentially small complex exponential current of the form $\frac{du}{uZ(u)}\epsilon^{ut}$, and the actual current consists of the synthesis of these components as expressed by

$$i(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{\epsilon^{ut}}{uZ(u)}\,du \tag{24}$$

From analogy with eqs 20 and 21 it is evident that

$$\frac{1}{uZ(u)} = \int_{0}^{\infty} i(\lambda)\epsilon^{-u\lambda}d\lambda \qquad Re\ u > 0 \tag{25}$$

Equation 24 gives the solution for $i(t)$ *explicitly*, but as a line integral in the complex plane. The path of integration is a line extending from $c - j\infty$ to $c + j\infty$ parallel to the imaginary axis and in the right-half plane. It is offset from this axis by an amount c sufficiently great so that all values of u that make $\frac{1}{uZ(u)}$ infinite (i. e., all the poles) lie to the left of the path. With $t<0$ the result of the integration is zero. With $t>0$ and $Z(u)$ a rational function, the result of the integration is equal to the sum of the residues at each of the poles—as though the path were actually a closed contour such as a circle about the origin of radius sufficiently great to include within it all these poles. Some knowledge of residue theory is necessary to use this integral.

A variation of the line integral of eq 22 which appears frequently for the unit function is

$$1 = \frac{1}{2\pi j}\int_{L} \frac{\epsilon^{ut}}{u}\,du \tag{26}$$

and correspondingly for the current resulting from unit function

$$i(t) = \frac{1}{2\pi j}\int_{L} \frac{\epsilon^{ut}}{uZ(u)}\,du \tag{27}$$

Symbol L designates a path from $-j\infty$ to $+j\infty$ along the imaginary axis, except at singular points on this axis. Here it passes around the point by a small half circle extending out into the right-half plane. For example, in eq 26 $u = 0$ is a pole at the origin, and L passes around the origin by a small hook to the right. In eq 27, if any values of u making $\frac{1}{uZ(u)}$ infinite are pure imaginaries or zero, they lie on the imaginary axis and must be avoided, each individually by small hooks to the right in the path L. These integrals are occasionally referred to as "hook" integrals. Equation 27 gives the same result as eq 24 except for integrals where poles of $\frac{1}{uZ(u)}$ fall to the right of the imaginary axis, but such cases are not of common occurrence.

Equation 25 gives $i(t)$ *implicitly*. With the unknown appearing as a function under the integral sign, it is an integral equation of the Laplace type. Equation 24 is a formal expression of its solution.

The 2 eqs 2 and 4 given earlier in surveying the

history of operational calculus are structurally the same as eqs 24 and 25. To show that they express relations of greater generality than might appear were the symbols for current, voltage, and impedance retained, the general functions $h(t)$ for the real variable t, and $\frac{1}{H(u)}$ for the complex variable u, were used. It may be seen that while Carson based his treatment of operational calculus on an integral equation, and Bromwich and Wagner based theirs on a complex line integral, these 2 defining equations stand in complementary relation to each other as the 2 aspects of analysis and synthesis of the generalized Fourier integral.

Summary of Operator Transformations

With the aid of the Fourier integral it is possible to establish operational calculus upon a strictly rational basis. The interpretation of operational processes, and permissible transformations of operators all can be determined from the corresponding treatment of transforms. These rules governing the use of operators constitute a summary of the subject. While the user must supply the imagination for their application, they can provide him with assurance that his course is sound. They are more fundamental than a table of operational formulas, since by applying them to a few cardinal equations the entire content of such a table can be built up.

While either the complex line integral or the integral equation can be used as a medium for developing the rules of operational calculus, the integral equation serves better because it involves mathematics more familiar to the engineer. Of the relationships given later, all except Nos. 4 and 5 can be derived from this equation by performing on it simple operations of ordinary calculus. These 2 exceptions are derived from the double Fourier integral.

In Table I are summarized the fundamental operator transformations. They are based particularly upon the works of Carson, van der Pol, and Campbell and Foster. The defining equation is given at the head of the table, and upon restoring the parts of the integral that are omitted thereafter each entry becomes of exactly this form. The expression $\frac{1}{H(u)}$ is the generating function corresponding to the operator $\frac{1}{H(p)}$. In the left-hand column are listed 17 transformations of $\frac{1}{H(u)}$. To each corresponds a new operator which, when applied to the unit function, gives the associated time function of the right-hand column. At the end are listed 3 useful equalities applying to operational equations.

The relations are written in terms of the complex variable u, and not the operator p, in order to avoid a dual interpretation of the symbol p. Symbol t stands for any real variable, but usually it represents time; a restriction to $t \geq 0$ is understood for each entry. The symbol a is either a constant or some additional independent variable.

In the following comments, the numeral references are to the entries in Table I:

Item 1 is applied in the most common processes, such as expansion in series and partial fractions, where the object is to break up the operator into a sum or difference of more easily recognized terms.

Item 2 states that factors independent of p or t participate as coefficients.

Item 3 governs a change of time scale.

Item 4 is known in the literature as Borel's theorem, and is the basis of Carson's development; it is another way of expressing the Boltzmann-Hopkinson superposition theorem, also Duhamel's integral. It interprets the product of 2 operational factors when the time equivalent of each taken separately is known. Note that the result is *not* the simple product of the 2 time equivalents, also that factors of operators are commutative.

Item 5 states that the operator equivalent to the product of 2 time factors can be formed if the operator equivalent of each taken separately is known. Note that the result is *not* the simple product of the 2 operator equivalents, but requires a line integration in the complex plane. An operator corresponding to instantaneous power could be derived in this way, letting $h_1(t)$ and $h_2(t)$ represent potential and current.

Item 5*a* is an alternative to 5, but is limited to cases where $h_1(t)$ can be expanded in a series of positive powers of t.

Item 6 interprets p^{-1} acting singly, showing it means integration with limits 0 and t. It is obtained from item 4 with $h_2(t) = 1$. If the complex line integral is used for developing these rules, p^{-1} is found to mean integration with limits $-\infty$ and t. This is immaterial in actual application provided $h(-t) = 0$, as it generally does in physical problems.

Item 7 is obtained by integrating once by parts. It interprets p acting singly, showing it means more than simple differentiation; if $h(0) \neq 0$, an impulse term $h(0)p\mathbf{1}$ must be appended, and not discarded until the final result is reached. Operational calculus deals with functions involving discontinuities in magnitude and slope, and its operators apply to these functions *in entirety*. If interpretation is derived from the complex line integral, p appears to mean simply differentiation. However, there is no disagreement actually, for if $h(0) \neq 0$ and the complex line integral for $\frac{d}{dt}h(t)$ is formed this integral must be broken up into 2 integrals for evaluation. One gives the impulse at the origin; the other gives the derivative of the continuous portion.

Items 6 and 7 disclose fundamental differences between operational calculus and ordinary calculus. In the latter the operation $\frac{d}{dt}$ and $\int_0^t dt$ applied to $h(t)$ are not commutative unless $h(0)=0$. In the former, by adopting item 7, p and p^{-1} are inverse operators, and commutative. This means $p.p^{-1}h(t)\mathbf{1} = p^{-1}.ph(t)\mathbf{1} = h(t)\mathbf{1}$. A distinctive feature of operational calculus is its conversion of a problem of calculus to one largely of algebra. Its operators can be interpreted, as here, so as to obey the commutative, distributive, and associative laws, and the law of exponents. Not all writers adopt the interpretation given in item 7. Consistency is maintained then by some supplementary rule. For example, Jeffreys states that when p and p^{-1} both occur in an operator, the p^{-1} operation must be carried out before the differentiations.

The important difference between the operator p and $D = \frac{d}{dt}$ of ordinary calculus is presented by Sumpner as follows ($\mathbf{1}$ is added here for uniformity):

$$D(at+b) = a \qquad p(at+b)\mathbf{1} = (a+bp)\mathbf{1}$$
$$D^{-1}a = at + b \qquad p^{-1}a\mathbf{1} = at\,\mathbf{1} \tag{28}$$

In operational calculus, p operating on a constant times unit function is an impulse, and not zero. Impulse terms are not discarded without supplementary analysis. This troublesome point arises in fractional-order asymptotic series expansions, where integration in the complex plane provides the justification.

Item 8 substantiates transformations involving exponential time factors which Heaviside called "shifting." It is obtained by change of parameter u to $(u + a)$. Many variations can be made of item 8 giving convenient rules for inserting in, or extracting from, operators time factors of exponential form, and for shifting such time factors

between operand and coefficient. These rules are convenient since operators are not commutative with time functions. Four transformations based on item 8 are:

If

$$\frac{1}{H(p)}\,1 = h(t) \tag{29}$$

then

$$\frac{1}{H(p-a)} \cdot \frac{p}{p-a}\,1 = \epsilon^{-at}\,h(t), \tag{30}$$

$$\epsilon^{-at}\frac{1}{H(p)}\,1 = \frac{1}{H(p+a)}\,\epsilon^{-at}\,1 \tag{31}$$

$$\frac{1}{H(p)}1 = \epsilon^{-at}\left[\epsilon^{at}\,h(t)\right] = \epsilon^{-at}\,\frac{1}{H(p-a)} \cdot \frac{p}{p-a}\,1 \tag{32}$$

$$\frac{1}{H(p)}\,\epsilon^{-at}\,f(t)1 = \epsilon^{-at}\,\frac{1}{H(p-a)}\,f(t)1 \tag{33}$$

These are useful in the treatment of traveling waves and their reflections. They are the basis of the operational treatment of rotating a-c machinery transients whereby rotational effects are eliminated and the case reduced to one of static coupled circuits.

Items 9 and 10 are variations of 8.

Item 11 defines Heaviside's "transfer" operator ϵ^{-ap}. It is obtained by change of variable from t to $(t-a)$ with attendant change in lower limit from 0 to a. The transfer operator is powerful in dealing with transients in distributed systems. It can produce time delay, or shift of reference coördinates. It can convert stationary functions to traveling waves, and conversely. Heaviside used it with an impulse, giving a function $\epsilon^{-ap}p1$ which is a unit impulse condensed at $t = a$, and zero elsewhere. With it he treated many problems of subsidence in distributed systems, evaluated difficult definite integrals, and established a connection between his operational processes and the work of Fourier.

Item 12 is established by differentiating with respect to a.

Item 13 is the complement of 12, and is established by integrating with respect to a. Items 12 and 13 state that differentiation or integration with respect to some variable in the operator other than p or t can be carried out freely. This is the basis of the operational solution of partial differential equations. Solution including fulfillment of boundary conditions is made first with respect to x. The result is an operator in p and x. Conversion into a function of t and x follows.

Item 14 is obtained by dividing by u, then differentiating with respect to u. In this and following cases is seen further advantage from using a complex variable u, instead of the operator p, in the statement of these rules. Differentiation or integration of an operator $\frac{1}{H(p)}$ with respect to p would be meaningless.

Item 15 is obtained by integrating once by parts, then differentiating with respect to u. Items 14 and 15 play important parts in recent developments; van der Pol applies them in extending operational processes to the variable coefficient class of linear differential equations, and Lowan employs their equivalent in solving partial differential equations with complicated initial and boundary conditions. As the transformations in items 14 and 15 can be repeated indefinitely, the operator equivalents of very general terms having powers of t for coefficients can be established. Values at the origin of $h(t)$ and its derivatives must be known for these more complicated cases.

Items 16 and 17 are complementary to 14 and 15; 16 involves the upper range of frequencies, while 17 involves the lower range. Each is obtained by dividing by u, integrating with respect to u, then applying 6. These have been used effectively by van der Pol in deriving operators for integral sine, cosine, and exponential.

Items 18, 19, and 20 are equalities provided the integrals exist; 18 and 19 are proved by integrating once by parts before passing to the limit. For 18 the integral $\int_0^\infty h'(t)dt$ must exist. Stated another way, $\frac{1}{H(u)}$ must have no poles on the imaginary axis, or in the right half-plane. Cases barred would be undamped trigonometric

Table I—Summary of Operator Transformations

$$\frac{1}{H(u)} = u\int_0^\infty h(t)\epsilon^{-ut}dt \qquad Re\ u > 0$$

1.	$\frac{1}{H_1(u)} \pm \frac{1}{H_2(u)}$	$h_1(t) \pm h_2(t)$	
2.	$a\,\frac{1}{H(u)}$	$ah(t)$	
3.	$\frac{1}{H\left(\frac{u}{a}\right)}$	$h(at)$	
4.	$\begin{cases}\frac{1}{u}\cdot\frac{1}{H_1(u)}\cdot\frac{1}{H_2(u)}\\ \frac{1}{u}\cdot\frac{1}{H_2(u)}\cdot\frac{1}{H_1(u)}\end{cases}$	$\int_0^t h_1(\lambda)h_2(t-\lambda)d\lambda$	
5.	$\frac{u}{2\pi j}\int_{c-j\infty}^{c+j\infty} F_1(v)\cdot F_2(u-v)dv$	$h_1(t)\cdot h_2(t)$	Where $\begin{cases}F_1(u) = \frac{1}{uH_1(u)}\\ F_2(u) = \frac{1}{uH_2(u)}\end{cases}$
5a.	$uh_1\left(-\frac{d}{du}\right)\cdot\frac{1}{uH_2(u)}$	$h_1(t)\cdot h_2(t)$	Provided $h_1(t)$ can be expanded in a series of positive powers of t
6.	$\frac{1}{u}\,\frac{1}{H(u)}$	$\int_0^t h(t)dt$	
7.	$u\,\frac{1}{H(u)}$	$\frac{d}{dt}\,h(t) + h(0)u$	
8.	$\frac{u}{u+a}\cdot\frac{1}{H(u+a)}$	$\epsilon^{-at}\,h(t)$	
9.	$\frac{u}{u+a}\cdot\frac{1}{H(u)}$	$h(t) - a\epsilon^{-at}\int_0^t \epsilon^{at}\,h(t)dt$	
10.	$\frac{1}{H(u+a)}$	$\epsilon^{-at}\,h(t) + a\int_0^t \epsilon^{-at}\,h(t)dt$	
11.	$\epsilon^{-au}\,\frac{1}{H(u)}$	$\begin{cases}0 & t < a\\ h(t-a) & t > a\end{cases}$	$a > 0$
12.	$\frac{d}{da}\,\frac{1}{H(u)}$	$\frac{d}{da}\,h(t)$	
13.	$\int_{a_0}^a \frac{1}{H(u)}\,da$	$\int_{a_0}^a h(t)da$	
14.	$-u\,\frac{d}{du}\,\frac{1}{uH(u)}$	$th(t)$	
15.	$-u\,\frac{d}{du}\,\frac{1}{H(u)}$	$t\,\frac{d}{dt}\,h(t)$	
16.	$\int_u^\infty \frac{1}{uH(u)}\,du$	$\int_0^t \frac{h(t)}{t}\,dt$	Provided the integrals exist
17.	$\int_0^u \frac{1}{uH(u)}\,du$	$\int_t^\infty \frac{h(t)}{t}\,dt$	Provided the integrals exist
18.	$\lim_{u\to 0}\,\frac{1}{H(u)} = \lim_{t\to\infty}\,h(t)$		Provided $\int_0^\infty h'(t)dt$ exists
19.	$\lim_{u\to\infty}\,\frac{1}{H(u)} = \lim_{t\to 0}\,h(t)$		
20.	$\int_0^\infty \frac{1}{uH(u)}\,du = \int_0^\infty \frac{h(t)}{t}\,dt$		Provided the integrals exist

or cisoidal oscillations. Item 18 shows that the low-frequency content of $\frac{1}{H(u)}$ determines the result at large values of t. This is applied in Heaviside's expansion theorem where the steady state term is written $\frac{1}{H(0)}$ by inspection. Item 19 shows that the high-frequency content of $\frac{1}{H(u)}$ determines the result at small values of t. This is applied in finding from the operator of a problem, initial values of the result and its derivatives.

Item 20 is the result of applying 18 to 16, or 19 to 17; van der Pol uses 20 to evaluate a variety of definite integrals.

Concluding Remarks

As many examples, fully worked out, showing the application of operational methods now can be found in textbooks and technical literature, such have been omitted here in order that attention might be concentrated upon the more fundamental aspects of the subject which give it rationality and cohesiveness. It has been necessary also to omit any discussion of asymptotic series expansions, as argument in terms of the integral in the complex plane is essential for their treatment.

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"Thyratron" Tubes in Relay Practice

The application of the grid-controlled gas-filled, or "thyratron," electronic tube to relay practice, principally for the protection of transmission lines, is considered in this paper. Several different types of these relays are discussed under the 2 principal classifications of "normal" design and high speed relays. This paper by Doctor Wideröe, based upon European practice, should be of considerable interest in this country.

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As SOON as the grid-controlled gas-filled (or mercury-vapor-filled) hot-cathode electronic tube was developed, it became evident that the tube would play an important part in the amplification of electrical impulses, where small quantities of energy are to be applied for controlling a comparatively large amount of energy for electrical apparatus of various kinds. In the majority of cases, however, this tube (designated "thyratron" tube by the General Electric Company, and "grid glow" tube by the Westinghouse Electric and Manufacturing Company) is not capable of controlling the energy continuously. That is, in contradistinction to the grid-controlled high-vacuum tube, the plate current of the grid-controlled gas-filled tube is not some continuous function of the grid bias, but immediately rises from zero to a maximum when the grid potential with respect to the cathode becomes more positive than a critical value which is termed the "firing potential" of the tube. Once the tube has been "fired," the plate current continues to flow as long as the plate potential is maintained, irrespective of any subsequent change in the grid potential. This discontinuous amplification characteristic is admirably suited for the application of this tube to relay practice. All of the grid-controlled gas-filled tube relays herein described have been developed and tested by the author at the A.E.G. relay factory, Berlin, Germany and are protected by patents in several countries.

The relay is an automatic sentinel at all times watching some electric value, for example, the magnitude of an electric current. When the current exceeds a definite, predetermined value, it is the duty of the sentinel to make this fact known by permitting a current to flow in a circuit which sounds an alarm or trips a circuit breaker. The function of the relay, therefore, is a double one; the first part consisting of measuring the current, and the second part to act as a discontinuous amplifier when called upon to do so. This second part of its function corresponds perfectly to the action of the grid-con-

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trolled gas-filled tube; and, furthermore, as the "firing potential" of the tube can be kept sufficiently constant, the grid circuit of the tube may be made to perform the first, or measuring function of the relay as well. It will be seen therefore, that the tube inherently possesses the fundamental properties required of a relay. In addition, this

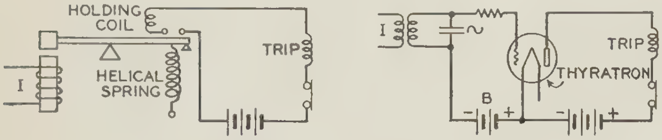


Fig. 1. Mechanical and thyratron instantaneous overcurrent relays

Symbol ∼ indicates that voltage across capacitor is alternating

relay possesses the following principal advantages as compared to "mechanical relays."

1. Quick action.
2. Small consumption of energy.
3. Absence of contacts or moving parts.

In the following, the counterparts in this tube relay of the more common forms of mechanical relays will be described together with a brief discussion of some of the limiting features and advantages.

Thyratron Relays of Normal Design, With Electrically Fixed Grid

The overcurrent and undervoltage relays in various forms and combinations, constitute the basis of all of the normal "thyratron" relays.

Overcurrent Relay

One design of a mechanical instantaneous overcurrent relay and the corresponding thyratron relay is shown in Fig. 1. While there are other forms of the mechanical relay, the one shown has been chosen because its several parts have their equivalents in the electronic relay. As shown, this mechanical relay consists of a double balance lever with a set of contacts and a fixed stop. A helical spring holds the lever against the stop and keeps the contacts open. At the other end of the lever is placed an armature which is attracted by an electromagnet, energized by the current to be measured. When the current rises to a predetermined limit, the force of the magnet overcomes the tension of the spring, and the lever turns on its pivot, closing the contacts.

Considering the thyratron counterpart, the thyratron tube is placed in the tripping circuit, and consequently a constant voltage is maintained between its anode and cathode. The tube will therefore "fire" and the tripping current flow when the voltage between the grid and cathode exceeds a certain value. This voltage between the grid and cathode corresponds to the balance lever in the mechanical relay. The battery B is connected in the grid circuit, so that the grid potential is negative and lies under the 'firing potential." This battery, therefore, corresponds in its action to the helical spring, or restraining force, of the mechanical relay.

The current I to be measured is arranged to produce an alternating voltage in the grid circuit through a current-voltage transformer (a transformer designed to produce a secondary voltage proportional to the current flowing in the primary). This transformer corresponds to the electromagnet of the mechanical relay. In its positive half cycle, the alternating voltage brings the grid potential nearer to the firing point. When the strength of the current exceeds a certain value, therefore, the grid potential will reach the firing point at the maximum value of the alternating voltage, and the relay will operate.

The action of the overcurrent relay has been described in considerable detail because it is typical of the operation of the majority of thyratron relays. The balance lever is always represented by the grid potential. As long as this potential lies below the firing point, the relay remains inactive, but when the firing point is reached, even for only a short time, the relay will operate. The operation of this relay, therefore, depends only upon the instantaneous relationship between the various voltages appearing

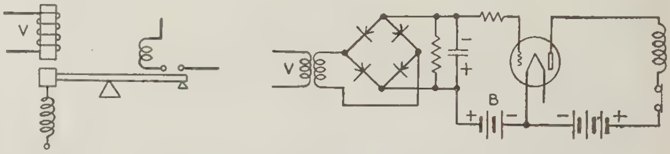


Fig. 2. Mechanical and thyratron undervoltage relays

in the grid circuit, and in this circuit will be found the vital design of the relay.

Undervoltage Relay

In Fig. 2 is illustrated an undervoltage relay, a relay which is brought into action when the voltage falls below a certain value. Contrary to the arrangement of the overcurrent relay just described, the counter force is now arranged so that it tends to close the tripping contacts or to fire the tube. The voltage to be measured acts as the restraining force.

It is evident that in the case of the thyratron relay the alternating voltage to be measured must be rectified (by rectifiers of the copper oxide or selenium type) and filtered since it must be introduced as a direct voltage into the grid circuit of the tube. The mechanical relay does not require voltage rectification since the restraining force is a function of V^2 which is the equivalent as far as the operation of the relay is concerned. As a rule the filtering effect is cared for by the inertia of the balanced beam.

A principal difference between the mechanical and thyratron relays will be noted:

The mechanical relay operates on the effective values of current or voltage and the counter force must be adjusted for the square of the current or voltage.

The thyratron relay operates on the maximum value or some function of the arithmetical mean value of the current or voltage (de-

pending upon the performance of the filter) and the counter voltage must be adjusted for the linear value of the current or voltage.

A considerably distorted current or voltage wave, therefore, may act unfavorably on the tube relay. On the other hand, this relay offers advantages over the mechanical relay when it is necessary to be able to adjust the tripping values of the relay over a wide range.

Under-Impedance Relay

By combining the 2 types of relays just described, the result is a "quotient" relay. The mechanical relay as shown in Fig. 3 compares the mechanical forces of the currents or voltages constituting the quotient. In the tube relay, the different voltages are connected in series and the comparison takes place in the grid circuit of the tube. The action of the relay is evident from the illustration and the descriptions given previously.

The under-impedance relay shown in Fig. 3 compares a current I and a voltage V. It will operate, therefore, when the impedance $\frac{V}{I}$ decreases below a fixed, adjusted value. The voltage V is rectified and operates as the restraining force while the current I furnishes a voltage tending toward operation. In the mechanical system a helical spring has been added to counteract the weight of the armature so as to bring the beam into balance with no magnetic forces applied. In the tube relay the battery B

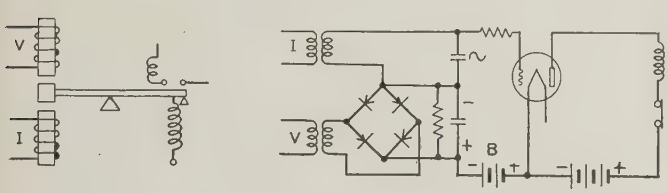


Fig. 3. Mechanical and thyratron under-impedance relays

Symbol ∼ indicates alternating voltage

serves the same purpose, causing the firing point to coincide with zero resultant voltage in the applied circuits.

Percentage Differential Relay

Such a quotient relay can be used as a "percentage differential" relay to measure the quotient $\frac{I_1 - I_2}{I_1 + I_2}$ where I_1 and I_2 are the currents measured at the terminals of the apparatus protected. This is illustrated in Fig. 4. A rectified restraining voltage proportional to the restraining current $(I_1 + I_2)$ is applied to the grid circuit of the tube. The tripping voltage is proportional to the differential current $(I_1 - I_2)$. This voltage is also rectified and the resistors and condensers used in the circuit must be selected to obtain a time constant for the tripping voltage greater than that for the restraining voltage.

A modification of the thyratron differential relay described is admirably suited to differential protection of transmission lines by the use of a-c pilot wires, in which case the energy consumption of the differential relay must be reduced to a minimum. The energy consumption of the thyratron relay is very small and depends entirely upon the design and form of the grid circuit. It is not difficult to keep the energy consumption as low as 0.0001 va or $\frac{1}{1{,}000}$ of what a very sensitive mechanical relay requires. This fact indicates the possibilities offered by the relay in the field of differential protection.

Distance Relay

The thyratron tube is readily adapted to distance relay work. Distance relays as a rule are very complicated, consisting of a number of moving parts;

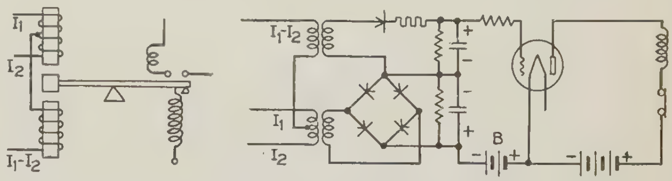
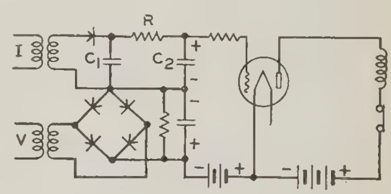


Fig. 4. Mechanical and thyratron percentage current-differential relays

and as a result leave something to be desired in the way of technical perfection and the absolutely reliable operation which should be required for devices of such importance. A thyratron distance relay operating on impedance is illustrated in Fig. 5: It differs from the under-impedance relay of Fig. 3 in that the tripping voltage is rectified as well as the restraining voltage. The rectified tripping voltage appearing across the condenser c_1 charges the condenser c_2 through the resistance R, so that the time

Fig. 5. Thyratron distance relay



constant for the effective tripping voltage appearing in the grid circuit across condenser c_2 is comparatively large. The relay will release when:

$$\frac{V}{I\left(1 - e^{-\frac{t}{T}}\right)} \leq k$$

where $T = Rc_2$, the time constant of the circuit. For values of $t < T$, the expression $1 - e^{-\frac{t}{T}}$ varies substantially as $\frac{t}{T}$ so that the tripping time is proportional to the impedance.

$$t = \frac{T}{k} \cdot \frac{V}{I} = \frac{T}{k} \cdot Z$$

The very low energy consumption of the thyratron distance relay offers the great advantage that

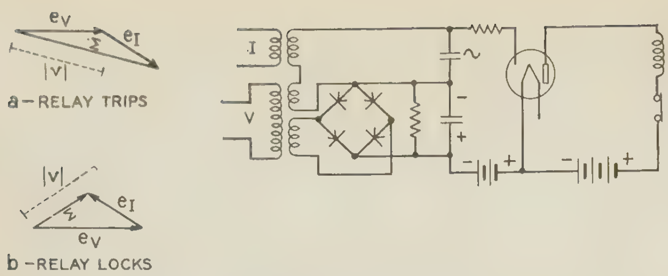


Fig. 6. Thyratron power directional relay

Symbol ~ indicates alternating voltage
ev indicates voltage derived from V
eI indicates voltage derived from I
|v| indicates scalar quantity

capacity potentiometers or condenser bushings can be employed in place of potential transformers as the source of secondary potential applied to the relay. This advantage may in many cases determine the selection of the protective system, especially in the case of very high line voltages.

The quotient relays so far described are all independent of the phase angle between the values compared. In many cases, however, relays dependent upon phase angles are required. This can be obtained by the suitable vectorial addition of the voltages in the grid circuit.

Power Directional Relay

A power-directional thyratron relay, a relay which operates when the power flow in a circuit is reversed, is illustrated in Fig. 6. The vectorial addition of a voltage derived from the current I and the voltage V works to trip the relay. The restraining voltage is obtained by rectifying the voltage V. When the current and voltage act in the same direction, the alternating voltage in the grid circuit becomes greater than the restraining voltage and the relay will operate. When the current flows in the opposite direction, the alternating voltage becomes smaller than the restraining voltage and the relay will not trip.

It should be noted that this relay may loose its directional discriminating ability under short-circuit conditions. If the ratio of the current to the voltage becomes sufficiently large, the alternating voltage in the grid circuit will always exceed the restraining voltage and the relay will release.

Reactance Relay

In Fig. 7 is illustrated a thyratron reactance relay which is approximately correct. Its action is much the same as that of the power-directional relay just described.

In order to obtain dependency upon reactance, the voltage V must be rotated 90 deg by means of a resonance circuit. The voltage rotated to this angle is connected in series with another voltage (designated k_1I) derived from the current, and the sum of these 2 voltages is rectified. The figure shows that the restraining voltage thus obtained, within certain limits for the phase angle θ, will be nearly equal to $k_1I + V \sin \theta$. An alternating voltage (designated k_2I) also derived from the current serves to release the relay. The relay will release when:

$$k_1I + V \sin \theta \leq k_2I \text{ or } \frac{V \sin \theta}{I} = X \leq k_2 - k_1$$

Therefore, the relay (within certain phase angles) will trip when the reactance falls below a certain value (under-reactance relay).

Relays of this type can be used for distance protection when a step-by-step characteristic is desired. A more perfect arrangement for this application, however, will be mentioned later.

Effect of Disturbances on Relays of Normal Design

The relays so far described all possess a number of common properties. They form a complete analogy to the common mechanical relays with balance levers and may therefore be designated as "normal relays." The principal properties of these normal relays is that they are comparatively little influenced by electrostatic disturbances. This property is of great importance in the correct functioning of the grid-controlled gas-filled tube (thyratron) relay.

Electrical disturbances, such as line surges, high frequency oscillations (radio waves) and transients in the d-c circuit may easily force themselves into the lines connecting the tube with other equipment and ultimately reach the grid of the tube. If they are able to change the grid potential appreciably, incorrect tripping may result. These electrical disturbances in the tube relay correspond to knocks or blows in the mechanical relay. In order to make the mechanical relay insensitive to disturbance of this nature, the balance lever must possess a comparatively large mass which tends to make the relay sluggish and slow.

In the tube relay of normal design, the same effect is secured by arranging a condenser of sufficient capacity between the grid and the cathode. In the majority of cases the filtering condensers used in the restraining elements can be arranged so that they prevent electrostatic disturbances. One might say that the grid potential is "tied" to the cathode by means of condensers. The relay will, of course, become correspondingly sluggish and slow but as the tripping time of most of these relays is governed by the speed of response of the restraining voltage, which, as a rule will be greater than one cycle, a tendency toward sluggishness in the tripping voltage is of no consequence.

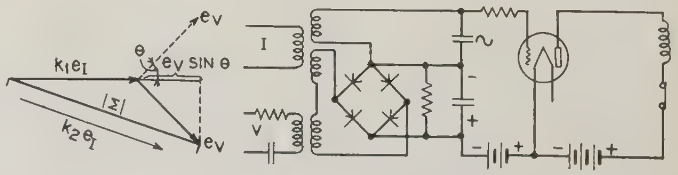


Fig. 7. Thyratron under-reactance relay

Symbol ~ indicates alternating voltage
ev indicates voltage derived from V
eI indicates voltage derived from I
|Σ| indicates scalar quantity

High Speed Thyratron Relays With Instantaneously Acting Grid

High speed thyratron relays can be built as well as high speed mechanical relays. High speed thyratron relays are characterized by a grid which instantly follows the momentary values of alternating voltages applying to it, and which releases without delay at the right moment.

The fundamental basis for these high speed relays involves an entirely new principle in relay operation, but which bears a certain similarity to the so-called Joubert principle for point to point measurement of a-c waves. This method consists of the use of a rotating contact for connecting a voltmeter for a very short time at the point of the a-c wave which is to be determined. By the successive displacement of the rotating contacts to other points on the wave, the form of the whole wave can be determined.

In the case of the high speed relay, a restraining voltage is introduced into the grid circuit, sufficiently high to prevent, beyond question, the relay from releasing. This counter voltage, however, is made to disappear periodically for a moment, and during this short time interval the relay is given an opportunity to measure the momentary value of an alternating voltage also applied to the grid circuit. By displacement of the phase of this periodically disappearing counter voltage or "test voltage," the relay can be made to measure the alternating voltage at any point on the wave.

High Speed Power Directional Relay

A high speed power directional thyratron relay which acts according to this principle is shown in Fig. 8. The test voltage is derived from the current circuit through a full wave rectifier. It produces a restraining force which disappears twice during each complete cycle. By using a current-dependent resistance such as "thyrite," the moment during which the voltage disappears—the testing moment—will be very short, and the testing voltage rises immediately thereafter to such a magnitude that the tube is unable to release under any circumstances.

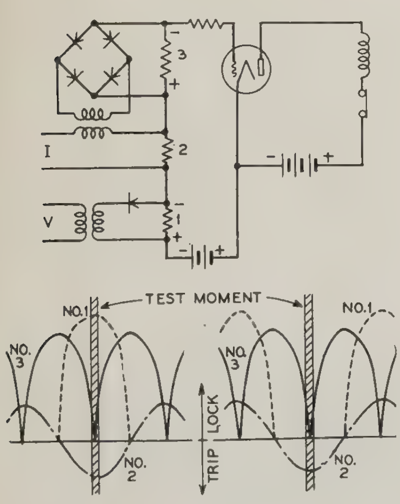
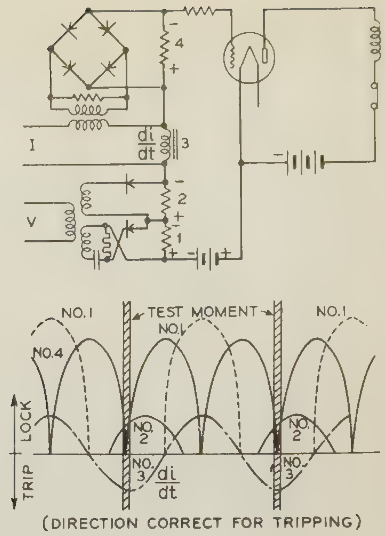


Fig. 8. High speed power directional thyratron relay

Fig. 9. High speed thyratron under-reactance relay with directional control



In addition to the test voltage, there are also acting in the grid circuit of the tube, a voltage proportional to the current I and a directed voltage (by half-wave rectification) proportional to the voltage V. As shown in the figure, the test moment is displaced 90 deg in relation to the current. The test consequently takes place when the current is at its maximum value, and the grid voltage due to the current will in one test moment act in the tripping direction, and in the next test moment, in the direction to lock. Whether or not the relay releases depends upon the directed counter voltage. If this is in action at the test moment when the current tends to release the relay, the release will be prevented. If it is action at the other test moment, however, the relay will release.

It will be found that the relay will lock from nearly +90-deg to −90-deg phase displacement between the current and voltage, provided the test moment is very brief and the directed counter voltage is sufficiently great.

This directional relay is well adapted to carrier-current pilot protection of transmission lines.

High Speed Reactance Relay

A high speed reactance relay especially designed for distance protection according to the step-by-step principle is illustrated in Fig. 9. Contrary to the relay just described, the test voltage here works in phase with the current I. The testing moment will always occur, therefore, when the current is zero. An induced voltage $\left(\text{designated } \frac{di}{dt}\right)$ produced by the current flowing through an unsaturated iron core reactor acts in the direction of release. The directed voltage V acts as the counter voltage. Assuming that the circuit which the relay is to control consists of a resistance R and an inductance L, the instantaneous voltage across the circuit v will amount to:

$$v = iR + L\frac{di}{dt}$$

Since, in the testing moment, i is zero, the counter

voltage v is consequently equal to $L \frac{\mathrm{d}i}{\mathrm{d}t}$, and this counter voltage is now compared directly by the thyratron tube with the voltage built up across the reactor which is proportional to $\frac{\mathrm{d}i}{\mathrm{d}t}$. The relay therefore measures the inductance L. If L lies above a certain value, the tube will lock. If L decreases below this value, however, the tube will release.

It is of interest to note that in contradistinction to the normal relay previously described, the inductive measurement is correct within wide limits of phase angle and will therefore be substantially independent of the resistance R in the circuit under control (depending only upon how brief the testing moment can be made). Furthermore, the measurement will be independent of the wave form of the current and voltage and also the frequency. It is even possible to measure current-dependent inductances by giving the iron in the reactor the same characteristic as the inductances which are under control.

Directional control may be applied to this reactance relay by simply adding another directed counter voltage proportional to the voltage V which has a phase displacement such that it cannot prevent the measurement of the inductance when the energy flows in the tripping direction. If, however, the direction is reversed, this counter voltage (the directional voltage) will act in the determining test moment and prevent release.

It is important to note that the correct directional action of both of the high speed relays described is conditional upon the presence of line voltage in sufficient magnitude. While this is true of all directional relays, nevertheless the conventional directional relays are slow or inoperative when the line voltage falls to a very low value due to the proximity of a fault, whereas the thyratron relays will operate irrespective of the fault direction and with no loss of speed. This means that particular care must be exercised in applying this tube type of directional relays and it will often be necessary to step up the directional voltage.

Effect of Disturbances on High Speed Relays

As previously indicated, difficulties may arise from surge voltages entering the grid circuits of the high speed tube relays and thereby causing false tripping. In the tube relays of normal design, this difficulty has been overcome by placing a condenser between the grid and the cathode, but in the case of high speed relays, it is impossible to "tie down" the grid in this manner. It is, therefore, necessary to protect the relay against surges with filters, blocks, and by-pass condensers.

To study this very important phase of the problem, the author built an extremely sensitive resonance relay with a freely acting grid. This relay was of the quotient type and was designed to protect the windings of a generator against ground faults. The tripping element of the grid circuit was tuned to resonance at the generator frequency (50 cycles) and the relay operated on approximately 10^{-6} va.

Due to the usual disturbances from the factory supply, the tripping of the relay was very unstable and the surges introduced potentials of nearly 100 volts in the grid circuit. By using high and low frequency blocks between the supply and the relay, the necessary grid biasing to compensate for surges was brought down to approximately one volt.

Conclusion

The grid-controlled gas-filled tube relays which have been described all work with a constant (within ± 10 per cent) anode potential, in which case the firing potential of the grid has a constant value. It may be of advantage sometimes to use an alternating voltage between the anode and cathode of the tube. In this way a very simple phase-dependent relay (such as a directional relay) can be built by letting the current produce the anode potential while the voltage acts on the grid. Such a relay operates in a manner similar to the ordinary Toulon control. It will release or lock depending upon the phase displacement between the current and the voltage. This relay operates satisfactorily, only when the anode potential can be kept fairly constant and not varying within too wide limits.

The principal requirement which must be fulfilled by the thyratron tube when acting as a relay is that the operating characteristics remain constant, even during varying external conditions.

These tubes must thus be independent of temperature variations. This means difficulties for the tubes filled with mercury vapor. As a rule they will not work at temperatures below +20 deg C. It is therefore necessary to provide them with a thermal protection, or to maintain the temperature in the vicinity of the relay comparatively constant by means of a thermostat or a similar device.

The grid-controlled tubes filled with argon gas seem to offer several advantages. The pressure of the vapor in these tubes is essentially higher than in the mercury-vapor tubes. Further, the pressure changes very little within the temperature limits usually occurring in practice. The characteristic of the argon-gas thyratron is therefore practically independent of the temperature variations likely to be encountered in practice. The argon-gas thyratron tubes have the limitation that the potential difference between the electrodes must not exceed 500 volts, as otherwise discharges between the electrodes will occur which can give a false tripping of the relay. This is entirely satisfactory, however, when the tubes are to be employed as relays. The thyratron tubes must be built so that the emission centers on the cathode surface will not change during the operation. If this is done, the operating characteristics remain entirely constant during long periods of time.

Various grid-controlled gas-filled tubes of this type were proved to keep the ignition potential at a constant value within approximately 0.2 volt during several months. When the anode potential varies ± 10 per cent, the ignition potential will not vary more than approximately ± 0.5 volt.

The life of the tubes is estimated to be 5,000 hr,

provided the tubes carry the maximum rated anode current. This is of importance for regulating relays. The anode current of the protecting relays is practically always zero, and the cathode only is heated in these relays. Under such circumstances the life will no doubt be considerably longer and should satisfy all reasonable demands.

The tubes which have been discussed are designed for a cathode current of 0.1 amp continuously, but are able to carry 0.2 amp for short time intervals. Larger tubes are available which may be used to handle the tripping current of a circuit breaker directly, and which in turn are controlled by a smaller but correspondingly exact measuring tube of the grid-controlled gas-filled (or mercury-vapor-filled) type.

Overloading of Power Transformers

The A.I.E.E. transformer subcommittee* has planned an extension of the scope of the Institute publication relating to the operation of transformers to include recommendations for the short-time overloading of oil-immersed transformers in service. These recommendations take advantage of the heat storage capacities of the materials of the transformer to supplement present recommendations relating to the continuous overloading that is possible when the ambient temperature is lower than the standard ambient temperature. This report gives a brief review of the considerations upon which the proposed changes are based and includes the new material in the form in which the subcommittee has prepared it. It is submitted to the Institute for constructive criticism.

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UNTIL recent years, A.I.E.E. standards for transformers have been limited in scope to the establishment of a standard rated output under definite assumed conditions, with the temperature rise under continuous rated load limited to 55 deg C. The sole purpose of these standards is to establish a standardization of design and of test. Experience in actual operation has shown that with these rating standards in force transformers in general have had reasonably long, useful life.

Recognizing that extra output is available from a transformer in service when the ambient temperature is low, the Institute in 1930 established recommendations for loading transformers in service when ambient temperatures differed from those of the rating standards. These recommendations (A.I.E.E. Standards No. 100) do not establish standards of operating performance subject to guarantee and demonstration by acceptance test, but rather they are intended solely as a guide for the safe continuous overloading of transformers under specified conditions.

Within the past year the transformer subcommittee has planned to extend the scope of the standards still further and has prepared a schedule of overloads permissible for short periods of time. This report includes a review of the considerations that have formed the basis for the proposed schedule, and a proposed revision of A.I.E.E. Standards No. 100 to include them.

Temperature Considerations

Deterioration of the insulation used in a transformer is the fundamental consideration that must be taken into account in establishing permissible overloadings. Since deterioration is a function of both *temperature* and *time*, it is essential first to establish a safe and reasonable schedule of limiting temperatures for various periods of time. Having established these temperatures, it is a relatively simple matter to set up overload values.

For some time, 3 limits of winding temperature, corresponding to 3 different time-periods, have been established in A.I.E.E. Standards No. 13. These temperature limits are as follows:

95 deg C for continuous operation. This is the average temperature of the winding resulting from 55-deg rise above an ambient temperature of 40 deg C (A.I.E.E. Standard 13-200).

Full text of a report prepared under sponsorship of the transformer subcommittee of the A.I.E.E. committee on electrical machinery, recommended for publication by the A.I.E.E. committee on electrical machinery, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 21, 1934; released for publication July 10, 1934. *Not published in pamphlet form.*

* **Personnel of transformer subcommittee:** H. V. Putman, *chairman;* G. M. Armbrust, E. S. Bundy, J. E. Clem, B. Lanphier, H. C. Louis, A. C. Monteith, V. M. Montsinger, L. C. Nichols, E. D. Treanor, and F. J. Vogel.

160 deg C for the one-minute operation of grounding transformers (A.I.E.E. Standard 13-250 *c*).

250 deg C for 5 seconds and less. This is the maximum temperature limit permitted during short circuit (A.I.E.E. Standard 13-250).

Having these 3 established temperature limits, all of them verified by years of successful operating experience, it was possible to set up the following temperature limits for the short-time overloading of power transformers:

Time	Winding Temperature Limit, Degrees C by Resistance
Less than 5 sec	250
30 sec	180
60 sec	160
5 min	140
30 min	120
2 hr	105
Continuous	95

It has been found in laboratory research that the rate of mechanical deterioration of fibrous insulating materials doubles approximately for each 8-deg C increase of temperature, and conversely is halved approximately for each 8-deg C decrease of temperature. (See "Loading Transformers by Temperature," by V. M. Montsinger, A.I.E.E. Trans., v. 49, 1930, p. 776; and "Operating Transformers by Temperature," by W. M. Dann, A.I.E.E. Trans., v. 49, 1930, p. 793.) When starting with 250 deg for 5 sec, it is realized that the 8-deg rule results in a temperature in excess of 160 deg for 60 sec. At the same time, it is realized that emergency overloads of 1-min operation may occur more often than dead short circuits at the terminals of a transformer. For these reasons the limits appearing in the table have been chosen to give a wholesome degree of conservatism which is warranted when establishing general rules for overloading transformers. Based upon the limiting temperatures that have been established for some time by the Institute, it is thought that this schedule presents a logical and satisfactory basis for the emergency short-time overloading of power transformers.

Classes of Short-Time Overloads

In establishing the limitations for short-time overloading, the transformer subcommittee recognized that circumstances affect the character of the overload and that overloads accordingly should be classified with regard for such circumstances. For instance, emergencies resulting from disturbances on the system may give rise to overloads that are unexpected and unpremeditated; on the other hand, it is desirable or necessary occasionally to undertake overloads for short periods of time in accordance with some considered plan. With these considerations in mind, the subcommittee has set up 2 classes of short-time overloads, namely:

Emergency Short-Time Overload. An emergency short-time overload is an unexpected overload of limited duration caused by some unpremeditated disturbance of normal operation; it is to be regarded as an infrequent occurrence.

Recurrent Short-Time Overload. A recurrent short-time overload is one of limited duration that is undertaken in accordance with a premeditated plan; it is regarded as an occasional occurrence with steady-state temperature conditions restored before repetition.

Emergency short-time overloads, according to the plan of the transformer subcommittee, are considered to be infrequent and not recurrent at relatively short intervals. With this interpretation, the full value of limiting temperatures referred to in previous paragraphs may be used for this class of overloads without restriction. On this basis, emergency short-time overloads have been determined for various periods of time that are thought to be the maximum consistent with safety and conservatism.

Since recurrent short-time overloads may occur more frequently than emergency overloads, it is logical that the level of limiting temperatures should be lower. There are few established levels of limiting temperature for overloads of this character. However, a limit of 100 deg C for 2 hr has been established for some time for railway transformers (60 deg rise above 40 deg ambient A.I.E.E. Standard 13-200). Limiting temperatures for this class of overload finally were set in the form of a curve passing through the following points:

Time	Winding Temperature Limit, Degrees C by Resistance
Less than 4 min	110
20 min	105
2 hrs	100
8 hr or more	95

Determination of Permissible Overload

In order to make the use and application of the foregoing considerations as simple and practicable as possible, overloads that are permissible within the limiting temperatures were calculated for a wide range of time periods and arranged in tabular form. The permissible overload for a given time then may be read directly from the table. If one is interested in the permissible overload for some intermediate time period not given in the table, it may be obtained by plotting a curve through a few points on either side of the desired time period.

Steady state temperature conditions at the beginning of the overload naturally have an important bearing on the value of the permissible overload. For this reason, 2 different steady state temperature conditions have been recognized, one for operation at full load and the other for no-load operation with excitation applied. A method of interpolation to determine the permissible overload for intermediate initial steady state temperature conditions also is provided.

Ambient temperature conditions also affect permissible values of short-time overloads because they affect the ultimate winding temperatures. A method is provided to adjust the permissible overload to an ambient temperature that differs from the standard.

The plan of the subcommittee is to incorporate this new short-time overload information in A.I.E.E. Standards No. 100, which originally was provided for approved operating practice.

Verification of the Proposed Permissible Overloads

Calculations made by transformer designers with a great many transformers of various ratings have given reasonable assurance that standard self-cooled power transformers that conform with the requirements of A.I.E.E. Standards No. 13 will carry safely the short-time overloads included in the revision of A.I.E.E. Standards No. 100 without undue deterioration of the insulation.

In verifying the temperatures for the various permissible overloads, final temperatures were calculated with the formula given in paragraph 13-250, A.I.E.E. Standards No. 13, when periods of overload were of such short duration that the heat developed by the overload current could be assumed to be completely stored within the copper. For longer periods of time, when the dissipation of heat from the copper becomes appreciable, final temperatures were checked by calculating both the temperature rise of the oil and the temperature rise of the winding above that of the oil, with formulas of the following form:

$$\theta = \theta_f\,(1-e^{-Bt}) \qquad B = \frac{W}{C\,\theta_f}$$

where

θ = temperature rise at end of time "t"
W = loss in watts
C = thermal capacity of the material that absorbs the dissipated heat
θ_f = temperature rise that would be attained with loss W continuously maintained
e = base of Naperian logarithms

Recommendations for the Operation of Transformers—A.I.E.E. Standards No. 100

According to the plans of the transformer subcommittee, A.I.E.E. Standards No. 100 will be revised and expanded to include the new material for short-time overloading as follows:

100–3. Continuous Operation at Rated Load.

This paragraph is to be used as it appears in Standards No. 100 but the word "continuous" is to be added to the heading to differentiate it from short-time operation.

100–4. Continuous Operation With Cooling Air and Water Exceeding 40 Deg C and 25 Deg C, respectively.

The word "continuous" is also to be added to the heading of this paragraph.

100–5. Continuous Operation at Loads Greater Than the Rated Load.

The word "continuous" is also to be added to the heading of this paragraph, which through typographical error is called **100–4** in Standards 100.

100–6. Short-Time Operation at Loads Greater Than Rated Load.

(*a*) It is recognized that power transformers of the oil-immersed type, having continuous ratings that conform with the standards for rating, may be loaded in excess of their rated loads for limited periods of time. For the purpose of defining permissible overloads of this kind, two classes of short-time overloads are recognized, as follows:

1. *Emergency Short-Time Overload.* An emergency short-time overload is an unexpected overload of limited duration caused by some unpremeditated disturbance of normal operation; it is to be regarded as an infrequent occurrence.

2. *Recurrent Short-Time Overload.* A recurrent short-time overload is one of limited duration undertaken in accordance with a premeditated plan; it is regarded as an occasional occurrence with steady state temperature conditions restored before repetition.

(*b*) Self-cooled oil-immersed power transformers may be operated at specified overloads for limited periods of time in accordance with the values given in Table I.

Table I—Permissible Short-Time Loads for Self-Cooled Oil-Immersed Power Transformers at an Ambient Temperature of 40 Deg C

Duration of Load	Emergency Loads* Following Full Load**	Emergency Loads* Following No Load†	Recurrent Loads* Following Full Load**	Recurrent Loads* Following No Load†
2 sec	25	25	6.5	13
5 sec	14	16	4	8
10 sec	9	10.5	3	6
30 sec	5	6	2.2	4
60 sec	3.7	4.7	1.6	3.25
5 min	2.3	3	1.25	2.1
30 min	1.6	1.9	1.1	1.45
2 hr	1.25	1.4	1.0	1.2

* The overload values contained in the table are expressed in multiples of the continuous rating of the transformers; *e. g.*, the figure 25 indicates a load of 25 times the continuous rating.

** For the permitted loads in the columns headed "Following Full Load," it is understood that, prior to the overload, the transformer has been operating at continuous rated load and at an ambient temperature of 40 deg C for a period long enough to have established steady temperature conditions.

† For the permitted loads in the columns headed "Following No Load," it is understood that, prior to the overload, the transformer has been under normal excitation with an ambient temperature of 40 deg C, but without load current, for a period long enough to have established steady temperature conditions.

1. The permissible short-time load for an intermediate period of time not given in the tabulation may be obtained by plotting a curve through a few points on either side of the desired point.

2. If the steady-state load preceding a short-time overload, either emergency or recurrent, is less than full load, it is possible to increase the permissible short-time loads given in the columns headed "Following Full Load," because of lower initial temperature. Interpolation to determine permissible overloads corresponding to initial loads between "no load" and "full load" may be made on the basis of the square of the initial load, as follows:

$$\left\{\begin{array}{c}\text{Permissible}\\ \text{overload}\\ \text{with } X\\ \text{initial load}\end{array}\right\} = \left\{\begin{array}{c}\text{Permissible}\\ \text{overload}\\ \text{following}\\ \text{no load}\end{array}\right\} - \left\{\begin{array}{l}\text{Difference between overloads}\\ \text{following no load and full load}\\ \text{multiplied by the square of}\\ \text{the } X \text{ initial load expressed as}\\ \text{a fraction of full load}\end{array}\right\}$$

For example, if the steady state load preceding an emergency overload is 70 per cent of full load, permissible load for 30 sec will be: $6 - [(6 - 5) \times 0.7^2] = 5.51$ times continuous rating.

3. *Effect of Ambient Temperature on Short-Time Overloads.* The short-time loads of Table I should be reduced 2 per cent of continuous self-cooled rating below the recommended load for each degree that the temperature of the cooling air exceeds 40 deg C. The use of self-cooled oil-immersed transformers in cooling air exceeding 50 deg C shall be considered as special.

The short-time loads of Table I may be increased 1 per cent of continuous self-cooled rating for each degree that the ambient air is below 30 deg C, except that no further increases are to be made for ambient air temperatures lower than 0 deg C.

(*c*) Permissible short-time overloads for oil-immersed transformers of types other than self-cooled are not yet available.

Engineering Education

Is Meeting the Challenge

By introducing new courses and new methods of instruction, engineering education is meeting the challenge of industry to teach engineers how to solve problems involving economic and social as well as engineering aspects. A few of the steps already taken or contemplated in this direction by several leading engineering colleges are outlined in this paper.

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DURING the past year there has been much discussion of the demands of present day industry and the ways in which these demands may be met by the engineering colleges, both in the A.I.E.E. ("Industry Demands and Engineering Education" by L. W. W. Morrow, ELECTRICAL ENGINEERING, April 1934, p. 518–22, and discussion, Oct. 1934, p. 1418–22) and outside (papers and discussion at the Ithaca, N. Y., meeting of the Society for the Promotion of Engineering Education, June 1934). This article has been written to state a general solution of the problem as it now exists, and to describe briefly a few of the steps already taken or contemplated by institutions with which the writer is familiar, to achieve some of the objectives.

Need for Definitions of Engineering and Engineer

To avoid misunderstanding, it may be well to state at the outset the definition of engineering to which the writer subscribes. While there have been many restatements and elaborations, it is his belief that the simplest and most comprehensive definition of engineering is that contained in the charter of the Institution of Civil Engineers (London) dated 1828, in which what was then termed "civil" engineering—in contrast to "military" engineering—was defined as the "*art of directing the great sources of power in nature for the use and convenience of man.*" It is evident that this definition covers a knowledge of physical science, and at the same time includes the economic and social, or human, aspects of applying physical science for the benefit of human society.

Full text of a paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted July 31, 1934; released for publication Sept. 6, 1934. *Not published in pamphlet form.*

The definition of an engineer in terms of what he does would obviously be "one who practices engineering." For a more descriptive definition, particularly with regard to the broader aspects of an engineer's function or duty, one may refer to the definition of "professional engineer" in the Encyclopaedia Britannica. This states that "*the engineer is under obligation to consider the sociological, economic, and spiritual effects of engineering operations and to aid his fellowmen to adjust wisely their modes of living, their industrial, governmental, and commercial procedures.*"

Recently the Engineers' Council for Professional Development (E.C.P.D.) has found it advisable to proceed to define an engineer for legal purposes in terms of his preparation, experience, and knowledge as determined by examination. No doubt this was necessary not only because of the quacks who had assumed the title, but also because of the fact that engineering graduates often have been referred to as engineers. There may have been a time in the past when it was possible to give a student the broad general training in fundamental physical and social science, and the specialized knowledge of a particular field that justified giving him the title of "engineer" on graduation. If this were ever true, the time long since has passed.

It seems rather important today to distinguish, both in industry and in educational circles, between an engineering graduate, an engineer, and a person who uses engineering methods in other fields such as business.

Why a New Emphasis on Social Aspects?

From earliest times up to about the last 10 years, engineers always have been concerned primarily with production, transportation, or communication. There has never been a sufficient supply of manufactured goods or raw materials in the places they were wanted, and the engineer's work of directing the great sources of power in nature has been primarily that of providing more goods or services, such as transportation or electric power. There always has been a demand for a greater capacity to produce than existed at the time. Usually this has been because the technical means of production were inadequate. Up to very recent years, therefore, the engineer has devoted himself largely to the conquest of the physical difficulties associated with the application of natural science. The part of his work dealing with "the use and convenience of man" in many cases has been minor. Nevertheless, the social aspects of the application of power always have been within the engineer's domain!

As many of the technical problems that years ago confronted engineers have been approaching a complete solution, more of their work has concerned itself with the economic and social aspects of power application or communication. The results of this trend are shown in the opinions of practicing engineers as to what the nature of engineering education should be, as embodied in the report of the Society for the Promotion of Engineering Education on its investigation of engineering education. Other

studies of similar character have been made by individual colleges and universities. All of these indicate that more and more attention should be given in the schools to the social sciences, such as economics, business organization, history, psychology, and sociology.

Is Engineering Dominance Undesirable?

What interest should be dominant in a course, broadened as previously indicated, to train men for the staff and operating positions of industry? The writer believes it should be the engineering group, not because industry in the past has chosen men for these positions largely from engineering graduates, but because of the unique intermediate position of the engineering group when the engineering function is conceived in accordance with the initial definition of this paper.

An engineer, by that definition, is one who stands between the pure scientist on the one hand and the economist, sociologist, or business man on the other hand. If there should be "pure science dominance" of a course, it is probable that economics, business organization, psychology, and sociology would not have their proper places in the curriculum. They would be overbalanced by higher mathematics, theoretical physics, and technical specialities. If, however, there is "business dominance," too much of the curriculum is likely to be given over to descriptive courses dealing with economic or industrial organization as it now exists, and too little time will be spent on courses of a rigorous character that develop the student's ability to solve problems. Properly qualified engineering teachers, the selection of which men is a very important point in this program, are the ones to determine a reasonable compromise between these 2 points of view.

Problem Solving Ability—The Key

In answer to the question why trained men for staff and operating positions of importance in technological industry are best educated under the dominance of an engineering group, a simple answer can be given: *because engineering training develops the ability to solve problems.* Ask any university student how the engineering courses differ from those of other colleges, and he will reply "you have to solve a lot of problems." This does not mean, of course, that problems are not given in other fields, or that there is not a growing tendency in other fields to recognize the advantages of problems for instructional purposes. At the present time it is, and for some years to come will continue to be, a rather unique attribute of engineering courses.

In order to train young men to tackle problems effectively it would seem advisable to have the subject matter of the problems as simple, straightforward, and definite as possible, so that the attention of both student and instructor could be concentrated on the method of attack, rather than to have it divided between the attack and a discussion of the nature of the data, the possible variations in conditions, doubtful validity of assumptions, etc. Obviously the physical sciences present the most ideal material on which to start.

After the ability to solve physical problems has been developed, the student then may turn his attention with more profit to problems in the social sciences where the variables are much more numerous, the reliability of data are frequently in question, and more than one correct solution is not uncommon. This seems to be the easiest way of education for responsibility in a mechanized industry. It is not the only way, of course, for many able administrators and executives in technical industry never have received an engineering training.

It is likewise true that without alterations the methods of tackling engineering problems cannot be applied to social problems. It is a manifest error to simplify or twist social problems around so that simple engineering solutions can be obtained. The engineering student must be trained to realize the difference and exercise judgment in the application of detailed techniques of solution.

Another benefit derived from starting the training of the staff and operators of mechanized industry in the engineering field is that executives in business need as much of the investigatory attitude in dealing with industrial problems, as the engineer does in dealing with more scientific subject matter. In all of the leading engineering schools research activities are so prominent that this influence is bound to be felt by the students.

"Honors Courses" to Develop Professional Engineers

So far nothing has been said as to how future professional engineers, whose concern will be as much with physical science as with social matters, are to be developed. It would seem that the most promising way of doing this is by the use of "honors courses" such as have been operating successfully at the Massachusetts Institute of Technology and other schools. Under this plan those students showing particular aptitude are given the opportunity to pursue individual study at whatever rate they are capable, and in the direction that gives promise of developing their innate abilities to the greatest extent. The professional engineer more than any other, must have great initiative and the ability to work out problems by himself.

The "honors course" plan appears to offer an admirable way of selecting and educating men who will have these qualities. The results obtained seem remarkable compared with what usually is accomplished in regular classroom work. This plan, of course, is applicable as well to outstanding students whose interests are more economic or social than technical.

In the scheme proposed here there would be no differentiation of department between the training of the men to staff and operate industry, and those, who as professional engineers, would design machines or products of that industry. This single administration is believed to have a very definite value.

If the staff and operating members of an industrial organization have passed through the same basic

educational processes as the professional engineers in that organization, it is possible to hope for a degree of coöperation and mutual understanding of the other's point of view that could not be hoped for in any other way. Those engaged in the sale and application of a technical product cannot be expected to have, and it would not be desirable from the point of industry that they should have, the same point of view as the designer or as the production engineer. Each function must have its own "guiding star," but this does not mean that each can go its own way unrestrained. Organizations can make those compromises that are necessary for the best conduct of business when they are so staffed that the point of view of one department can be understood and accepted as reasonable by another. A great deal often can be accomplished if one group will grant that another group can hold a set of ideas different from that held by the first group regarding a business topic, without being a "bunch of half-wits." Much useless pulling at cross purposes could be avoided in technological industries if better understanding existed between different parts of their organizations.

Make-Up of a Modern Engineering Course

The question "What is the make-up of the course that will accomplish these results?" now will be answered. It will consist of a fundamental training in mathematics, chemistry, physics, the arts of expression, economics, business organization, psychology, history, and sociology. Depending on the field of engineering, there will be basic engineering courses dealing with electrical, mechanical, civil, or other branches. Options in advanced engineering courses will be provided. No required specialized application courses will be included in the 4-yr program. A considerable portion of the student's time will be available for elective courses, subject to reasonable advice and consultation with competent faculty members. In these elective courses the individual characteristics of the student will be amply recognized. Students show many different degrees of interest in the technical and social aspects of engineering. To be successful, any course must enlist their interest and abounding enthusiasm. The "honors course" will provide the method within each engineering department for the development of the relatively few individuals who have some hope of success as professional engineers.

School a Part of Real Life

In the elementary and secondary schools, it is being found that one of the surest ways to awaken the student to creative activity is to reorganize the way in which the school is conducted, so that it becomes a part of real life, and not an area of artificial experience, where people sit with folded hands and do not whisper to each other.

Not all the secondary schools by any means have accomplished this liberalization, so that it is now the job of the college to bridge the gap, if any, between the youth's previous school experience and real life in technological industry, and in a machine age generally. Particularly in the later years of the course, an effort should be made to have the work of the college correspond to real life. Individuals or groups of students would be assigned projects to be completed at specified dates. There would be very few formal lectures, but many round table conferences of committees assigned to related projects. A promising idea, tried out in a few places already, is to provide each senior student with a desk in the manner of large engineering offices, and even with stenographic service. The student is expected to spend a full day on the job, with a night or 2 of study at home each week—just the sort of thing he will do if he makes a success of his early professional career.

With this point of view, the transition from college to industry will be less painful to the individual, and less costly to industry. It will be but a step in progress, and not a revolutionary change. Much of the complaint that is heard of the attitude of young engineering graduates in industry thus will be eliminated.

It may be objected that the success of this program depends entirely upon the caliber of men in the engineering faculty who teach and administer it. The answer to this is that the value of any engineering course, past, present, or future, depends upon the caliber of the men teaching and administering the work.

Type of Faculty Required

To give the type of engineering course here described, the faculty members of the engineering departments must realize clearly the intermediate position in which the engineer stands between the pure scientist on the one hand and the economist, social scientist, or business man on the other. They must realize that it is not the function of an engineering course to train pure scientists, though some graduates may engage later in work of a purely scientific character. However, they must maintain the engineering character of the course, typified by problem solving, as against the necessarily descriptive character of many subjects in social science. At the same time they must have the ability to utilize the student's preparation in these other subjects so that in their own engineering courses the application, either through analysis or synthesis, of fundamental technical and social principles, which really constitute engineering, may be clearly brought out.

Teachers most likely to have properly balanced points of view are those who have had practical experience of some years in industry and who endeavor to maintain that contact during their teaching careers. This means that the criteria adopted in some educational institutions of hiring only those men who have obtained a series of academic degrees will have to be reconsidered, and worth while experience in industry rated the full equivalent of an academic Ph.D. degree.

A man who has done real engineering work in any large industry has unavoidably been impressed by

the necessity of coöperation between the different departments of the corporation. In fact he has seen that unless people coöperate, they are "fired." Such a man is, therefore, one who readily can appreciate the necessity of the coöperation that is essential between the pure science and the social science divisions and the engineering department. Experience usually will have taught him how to go about securing this coöperation.

The New Program Well Worth Its Higher Cost

A college that carries out the modern program of engineering education here proposed will educate young men first in the analysis of physical problems, accompanied by as much practice as possible in the synthesis or devising of new solutions. After some skill in problem solving technique has been acquired, students will attack engineering problems that embrace both technical and social fields.

A knowledge of those few principles of the physical and social sciences that are truly fundamental will be gained through a well balanced curriculum. The whole aim will be to make the college work an integral part of life. To teach the engineering subjects and administer the courses, particularly well qualified teachers will be needed. This new program may cost more per student than the conventional one, but the present demands for improvement are so insistent, and the product sure to be so much better, that they will amply justify the increased expenditure.

Heat Flow in Turbine Generator Rotors

The various factors which enter into a determination of the temperatures in turbine generator rotors are discussed in this paper, and a method of calculating temperatures is given. It is shown that a large number of variables can be taken into account in a relatively simple manner and that the method can be applied with accuracy to all sizes and types of turbine generator rotors.

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ACCURATE predetermination of turbine generator rotor temperatures is important from the standpoint of differential expansion of the coil and coil strands, and safe operating temperatures of the field coil insulation.

A reasonably complete and accurate analysis of temperatures in any electrical machine presumes a knowledge of the following factors:

1. An accurate method of calculation based upon an analysis which does not neglect the importance of the several fundamental variables involved.

2. The interaction of the separate parts, such as effect of end winding temperatures on the temperatures in the main body of the machine.

3. The magnitude and distribution of the various losses generated.

4. The ventilation characteristics of the machine, such as the distribution of velocities and amounts of air circulating through the numerous cooling paths.

5. An accurate knowledge based upon research and test experience of the physical constants used in the calculations, such as thermal resistivity of the insulation, contact resistances, and surface dissipation rates corresponding to the various velocities of the cooling medium.

The purpose of this paper is to combine the above factors into a reasonably complete analysis. The method of calculation for the temperature rises in the slot region of the rotor is based upon equivalent thermal circuits which have been worked out by C. R. Soderberg in his paper,[1] "Steady Flow of Heat in Large Turbine Generators." The circuits devised by Mr. Soderberg are based upon a complete theoretical analysis of the fundamental thermal paths in the slot region of a turbine generator. The circuits which are described later in the paper are based solely upon his work and a discussion of the basis of the circuits used is, therefore, omitted.

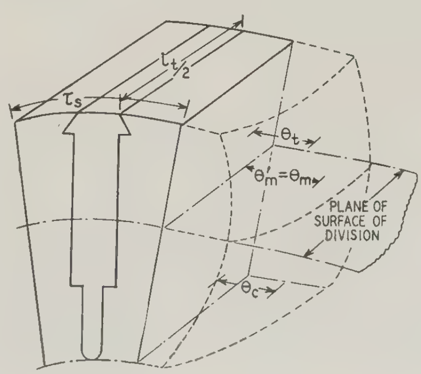

Fig. 1. Detail of slot region considered with surface of division and iron temperature distribution

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* The author has applied for Associate membership in the Institute.

1. For all numbered references see list at end of paper.

The main body of the paper outlines the general method of calculation and discusses the applications. The appendixes give a detailed picture of the calculation methods.

Method of Calculation

The complete steady state temperature analysis involves 3 principal steps, namely, the determination of the following:

I. Temperature rises in rotor body assuming no longitudinal heat flow along the conductors to the end windings or *vice versa*.

II. Temperature rises in the end windings assuming no longitudinal heat flow along the conductors to the rotor body or *vice versa*.

III. Longitudinal distribution of temperatures in the conductors along the complete length of the end windings and rotor body. I and II must be calculated in order to complete the calculation of III.

I. Temperature Rises in the Rotor Body

A detailed oblique sketch of the region considered in the calculations is shown in Fig. 1. This region is bounded on the rotor surface by an area equal to

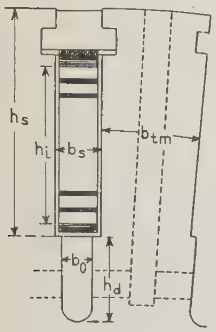


Fig. 2. Detail of slot region showing dimensions used in Figs. 3 and 4

$\tau_s l_t/2$. τ_s = distance between corresponding points on adjacent slots at the air gap (slot pitch) and l_t is the distance between radial ventilating ducts in the axial direction. The region is bounded on the sides by 2 radial planes intersecting at the center of the rotor. The type of ventilation considered is that containing an axial slot under the coil which leads to radial discharge vents.

The radial heat flow in the tooth region divides at an imaginary cylindrical surface, called the "surface of division," which denotes the radial location of the maximum iron temperature. Referring to Fig. 1, the surface of division is located correctly when the mean iron temperatures at the surface of division, calculated from outside and inside the assumed location, have the same value. That is, $\theta_m = \theta_m'$, where θ_m is the mean tooth temperature rise *at the surface of division*, using temperature rise constants derived from a solution of the equivalent thermal circuit which applies to the region outside of the surface of division. Similarly, θ_m' is the mean iron temperature rise at the surface of division derived from a solution of the equivalent thermal circuit inside of the surface of division. The distribution of temperatures in the iron of the tooth region is assumed to be parabolic in both the axial and radial directions. θ_t is the mean tooth temperature as represented by the mean height of the paraboloid of temperature distribution in Fig. 1 above the surface of division.

A detailed sketch of the slot region and diagrams of the equivalent thermal circuits outside and inside of the surface of division are shown in Figs. 2, 3, and 4.

The calculation of the mean temperature rises in the region being considered consists of combining the various thermal resistances in the circuits into "temperature rise constants." These constants when multiplied by the loss give the temperature rise. This is the thermal equivalent of Ohm's law.

The equivalent circuits are based upon the following assumptions:

1. All heat generated in the region defined in Fig. 1 flows through axial and radial paths to the vent ducts and air gap. This assumes that there is no longitudinal heat flow along the copper to the ends. The longitudinal flow will be discussed later in the paper.

2. Losses are generated uniformly.

3. Since the rotor is only partially slotted around its periphery, there is some heat flow in a tangential direction to the pole centers. This effect is approximated by distributing the cooling surface on the pole uniformly over the tooth tips in the slotted portion, thus restricting the problem to heat flow in 2 dimensions (axial and radial).

Symbols and Units of Figs. 3 and 4. In general, ρ with a descriptive subscript is the thermal resistivity in degree(Centigrade)-inches per watt, which is the inverse of thermal conductivity. C with a descriptive subscript is the surface resistance in degree(Centigrade)-inches[2] per watt, which is the inverse of surface dissipation. Each thermal resistance in Figs. 3 and 4 has the units of degrees Centigrade per watt. The losses generated in the region defined in Fig. 1 are expressed in watts. Hence, the product of loss and resistance gives the various temperatures in degrees Centigrade. Other systems of units may be applied without altering the form of the resistances dealt with in this discussion. A complete list of symbols for the circuits is given in Appendix I.

There are various methods of solving the circuits of Figs. 3 and 4, and the method outlined in this discussion is made consistent with Mr. Soderberg's treatment[1] in that the various resistances are combined and expressed as an over-all resistance called a "temperature rise constant," which has the units of surface resistance in degree(Centigrade)-inches[2]

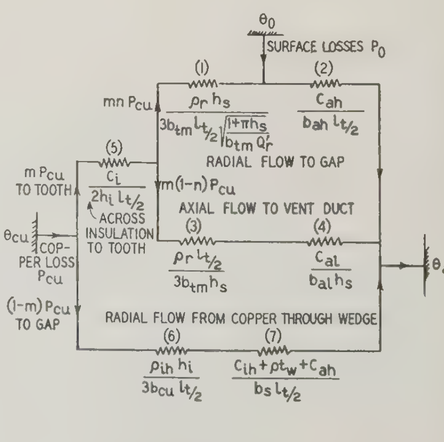


Fig. 3. Equivalent thermal circuit above surface of division

per watt. The various losses are expressed as watts per square inch of rotor surface at the air gap. If P_{cu} is the total copper loss in the region outside of the surface of division as defined in Fig. 1, then the loss in watts per square inch of rotor surface p_{cu} is obtained by the relation

$$p_{cu} = \frac{P_{cu}}{r_s l_t/2} \tag{1}$$

Solution of the Thermal Circuits. For the region outside of the surface of division, the mean temperature rises of the copper and tooth above ambient are:

$$\begin{aligned} \theta_{cu} &= \theta_a + p_{cu}\cdot C_{cu} + p_0 C_0 \\ \theta_t &= \theta_a + p_{cu} C_t + p_0 C_0 \end{aligned} \tag{2}$$

C_{cu}, C_t, and C_0 are temperature rise constants derived from a solution of the equivalent thermal circuit of Fig. 3 in Appendix I. p_{cu} and p_0 are the copper and surface losses. θ_a is the mean temperature rise of the cooling medium as it absorbs the losses while passing through the ventilating passages.

It is usually more convenient to evaluate the copper loss at a given temperature and apply a correction for the change in resistance. If the copper loss p_{cu} is based upon a temperature of 75 deg C, the mean temperature rises of eq 2 become

$$\begin{aligned} \theta_{cu} &= \frac{310}{310 - p_{cu}C_{cu}}\left[\theta_a + p_{cu}C_{cu}\left(\frac{235+\theta_0}{310}\right) + p_0C_0\right] \\ \theta_t &= \theta_a + p_{cu\theta}C_t + p_0C_0 \end{aligned} \tag{3}$$

where $p_{cu\theta} = p_{cu}\,\dfrac{235 + \theta_0 + \theta_{cu}}{310}$ and θ_0 is the ambient temperature.

Similarly for the region inside of the surface of division, the mean temperature rises of the copper in the slot, the iron in the tooth region, and the iron in the core above ambient are:

$$\begin{aligned} \theta_{cu} &= \theta_a + p_{cu}C_{cu} \\ \theta_t &= \theta_a + p_{cu}C_{cut} \\ \theta_c &= \theta_a + p_{cu}C_{cuc} \end{aligned} \tag{4}$$

C_{cu}, C_{cut}, and C_{cuc} are the temperature rise constants derived from a solution of the equivalent thermal circuit of Fig. 4 in Appendix I. p_{cu} is the copper loss inside of the surface of division, and corrections for change in resistance are carried out as indicated for eq 3.

It is sometimes of interest to know the loss distribution through the various parallel paths. In Fig. 3, the copper loss divides so that m parts flow across the slot insulation to the tooth and $(1-m)$ parts flow from the copper radially to the air gap. In the tooth, the m parts divide into n and $(1-n)$ parts to follow the parallel paths radially and axially to the air gap and vent duct. Expressions for m and n are given in Appendix I.

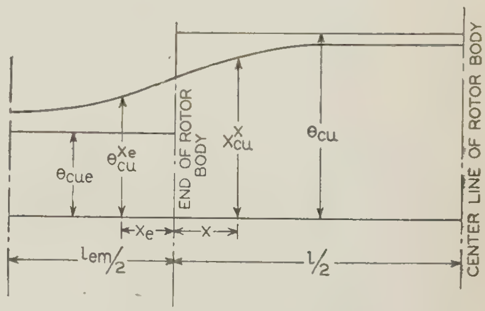


Fig. 5. Diagram of longitudinal temperature distribution

Relative thermal drops in various parts of the circuits can be obtained by the product of the thermal resistance and the loss component as given by the expressions for m and n.

Extent to Which Calculations Should Be Carried. If $\theta_m = \theta_m'$, the surface of division has been located exactly by "matching" the mean iron temperatures. The expressions for θ_m and θ_m' as defined in Fig. 1 are given in Appendix I. The copper temperature rise for the complete radial depth of coil is the weighted average of the value calculated for the outside and inside of the surface of division. In most calculations about the same accuracy is obtained by assuming the location of the surface of division at the midpoint of the radial tooth height and obtaining an average of the copper temperatures outside and inside the surface of division, even though the mean tooth temperatures at the surface of division are not exactly matched.

It is sometimes convenient to obtain an over-all temperature rise constant for the total radial depth of tooth. This can be obtained from the relation

$$C_{cu} = \frac{310(\theta^*_{cu} - \theta_a)}{p_{cu}(235 + \theta^*_{cu} + \theta_0)} \tag{5}$$

where θ^*_{cu} is the average copper temperature obtained from calculation of the copper temperatures outside and inside the surface of division. p_{cu} is copper loss at 75 deg C for the total slot depth.

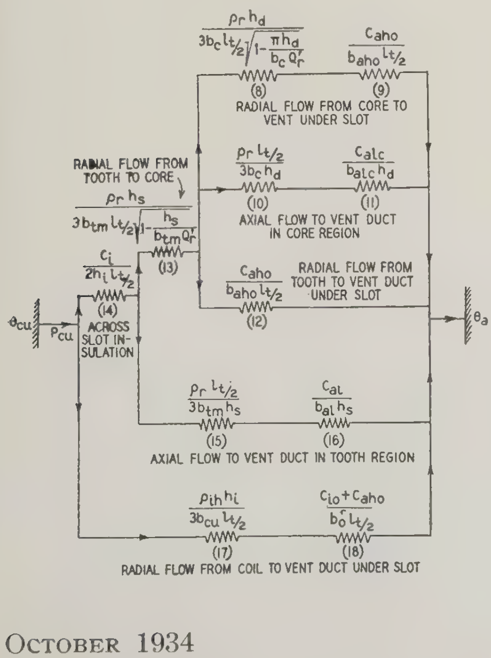


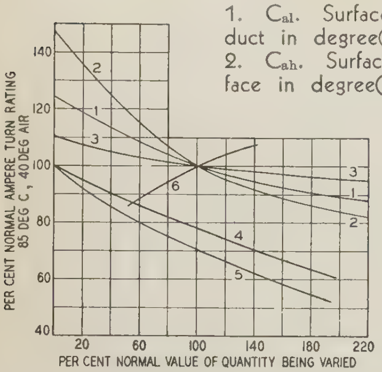
Fig. 4. Thermal circuit below surface of division

II. Temperature Rises in the Rotor End Windings

Rotors of modern construction are usually ventilated in the end turns by means of holes in the retaining rings and with or without special blocks between turns which increase the velocity of the cooling medium relative to the coil. In some cases, the sides of the coil on the ends are not insulated over their

total area so that bare copper is exposed to the cooling medium. A larger part of the coil sides not located near the ventilating passages is surrounded either by dead air space or filler material, which greatly increases the heat resistivity in these parts.

The temperature rises in the ventilated and nonventilated portions are calculated and the interaction of one on the other is accounted for in the same manner, as will be described under III, in which the longitudinal heat flow effects of the end windings and rotor body are considered. In this discussion, the interaction effects of the nonventilated and ventilated portions of the end windings are evaluated



1. C_{al}. Surface resistance of radial vent duct in degree(Centigrade)-inches² per watt
2. C_{ah}. Surface resistance at rotor gap surface in degree(Centigrade)-inches² per watt for nonventilated rotor
3. C_{ah}. Same as 2 except rotor is ventilated
4. P_0. Surface loss in watts per inches² of rotor surface, ventilated rotor, expressed as per cent of copper loss for 85 deg rise
5. P_0. Same as 4 except rotor is not ventilated
6. Peripheral speed based upon 26,000 ft per minute as 100 per cent

Fig. 6. Variation of ampere turn rating

and put in curve form. The method consists of calculating the temperature of the ventilated portion and altering the result by a factor F from the curves of Fig. 10, which allows for the heat flow from nonventilated portions. This greatly shortens the calculation of the end winding temperatures. The method of calculating end winding temperatures is given in Appendix II.

III. Longitudinal Temperature Distribution

Thus far the temperature rises of the rotor body and end windings have been considered neglecting the heat interchange between them. In many cases, there is considerable heat flow longitudinally in the field winding because of the difference in temperature between the ends and the rotor body. The fundamental equations upon which the following equations are based have been discussed before,[2] and therefore are not repeated here.

The mean copper temperatures at the points X and X_e are, respectively (see Fig. 5):

$$\theta_{cu}^{X} = \theta_{cu} - \frac{\theta_{cu} - \theta_{cue}}{1 + \dfrac{C \tanh Cl/2}{C_e \tanh C_e \dfrac{l_{em}}{2}}} \; \frac{\cosh C\,(l/2 - X)}{\cosh Cl/2} \qquad (6)$$

$$\theta_{cu}^{X_e} = \theta_{cue} + \frac{\theta_{cu} - \theta_{cue}}{1 + \dfrac{C_e \tanh C_e \dfrac{l_{em}}{2}}{C \tanh C\,l/2}} \; \frac{\cosh C_e\left(\dfrac{l_{em}}{2} - X_e\right)}{\cosh C_e \dfrac{l_{em}}{2}} \qquad (7)$$

in which θ_{cu} and θ_{cue} are the body and end winding temperatures neglecting longitudinal flow as given earlier in the paper under headings I and II.

$$C = \sqrt{\frac{\rho_{cu}\tau_s}{C_{cu}\cdot a_{cu}}\left(1 - \frac{p_{cu}\,C_{cu}}{310}\right)}$$

$$C_e = \sqrt{\frac{\rho_{cu}\tau_s}{C_{cue}\cdot a_{eu}}\left(1 - \frac{p_{cue}C_{cue}}{310}\right)}$$

The factor in parenthesis allows for change in temperature coefficient of resistance, on basis of 75 deg C

ρ_{cu} = thermal resistivity of copper, degree(Centigrade)-inches per watt
a_{cu} = cross section area of copper in slot (square inches)
l = axial length of rotor body in inches
l_{em} = length of mean turn on one end of rotor (inches)
= $^1/_2$ (total mean turn of winding $-$ $2l$)
X = distance along coil measured from end of rotor body
X_e = distance along coil on end windings measured from end of rotor body toward extremity of end winding

It is important to note that θ_{cu} and θ_{cue} enter into the equations for longitudinal heat flow. Thus, the accuracy of determination of the longitudinal heat flow depends directly upon the accuracy of the temperatures θ_{cu} and θ_{cue} which neglect the longitudinal heat exchange. It is important to determine θ_{cu} more accurately than θ_{cue} since the body temperatures influence a much larger proportion of the total coil length than the end winding. Usually the rotor temperatures are measured by means of change in resistance of the winding, the measurement corresponding to the mean temperature rise of the winding over its total length. This temperature can be obtained by integration of eqs 15 and 16 over the length of rotor body and end winding, which gives:

$$\theta_{cum} = \frac{l}{l + l_{em}}\,\theta_{cu} + \frac{l_{em}}{l + l_{em}}\,\theta_{cue} + \frac{2(\theta_{cu} - \theta_{cue})}{l + l_{em}} \cdot \frac{\dfrac{C}{C_e} - \dfrac{C_e}{C}}{\dfrac{C}{\tanh C_e \dfrac{l_{em}}{2}} + \dfrac{C_e}{\tanh Cl/2}} \qquad (8)$$

The method of calculation allows a complete study of the several variables involved, and which should be considered to arrive at an accurate determination of temperature for a large range of size and rating. In addition, the accuracy of determination depends upon the magnitude and distribution of the losses, knowledge of ventilation characteristics, and a knowledge of surface dissipation rates and conductivity constants which are based upon research and test experience on actual machines.

Losses

The electrical losses in the rotor consist of copper losses and surface losses. The copper losses depend upon the square of the current and resistance of the winding, and can be calculated accurately. The surface losses cannot be estimated accurately, but in the normal modern rotor, the surface losses are usually very small and have little effect on the copper temperatures. In single winding generators with unbalanced loads and double winding generators with unequal load division, the surface losses on the rotor may be of large magnitude, and will increase the copper temperatures considerably. This condition usually exists when the field current is a fractional part of the full load current, and the temperature rise in the copper due to surface loss plus

copper loss is no greater than the full load temperature rise.

Ventilation

A complete discussion of the ventilation characteristics of the rotor is beyond the scope of the present paper, but a brief note concerning the determination of the various vent duct velocities may be of interest. A complete study of the pressure drops through the ventilating circuit has been made on a rotating model of a turbine generator rotor. Additional tests on full size rotors were made to determine the ventilation effect by measuring the temperature rises and windage with and without ventilation in the rotor. From these investigations, data on average velocities in the various ducts were obtained.

Dissipation Rates

In addition to the determination of the magnitude of the velocities, the average dissipation rates corresponding to these velocities should be known. The rate of heat dissipation from the axial and radial vent ducts depends not only upon the magnitude of the velocity but also upon the length of the duct and the size and shape of its cross section. Some work of this nature with especial reference to the ducts in electrical machines has already been published.[4]

The dissipation rate from the rotor gap surface is practically constant for the range of high peripheral speeds at which turbine generators operate (22,000 to 28,000 ft per minute). At these speeds, the film of air rotating with the rotor is effective in preventing the heat transfer from increasing beyond a certain value. Other tests, though not conclusive, indicate that grooving the rotor surface increases the effective dissipation area only by a small amount.

The contact resistance between the coil insulation and the slot when it is assembled and has current flowing is decreased below the value that might be expected from the clearances indicated by the difference in dimensions between the slot width and coil width. Tests made on a full size coil indicated that the equivalent air layer was about $^1/_4$ to $^1/_3$ as thick as the clearance dimensions indicate, due to the effect of filler between the coil and slot and also to the swelling of the coil when heated.

Effect of Several Variables on Rating

Curves on Figs. 6 and 7 show the change in ampere turn rating of a representative large turbine generator rotor as the several variables enumerated below are changed over a large range of values. The 100 per cent value indicates the values of the variables for normal ampere turn rating. The effect of changes in the mean air temperature rise as the ventilation and losses are varied is taken into account in the calculation. The ampere turn rating is expressed for 85 deg C rise above 40 deg C air according to present A.I.E.E. standard.

Variation in Vent Duct Velocity. This affects the surface resistance to heat flow at the vent duct (C_{al}, Fig. 6). If the surface resistance is $^1/_2$ the value at 100 per cent rating, the ampere turn rating is increased 10 per cent. If the surface resistance is twice the value at 100 per cent rating, the ampere turns decrease 10 per cent.

Variation in Gap Surface Dissipation (C_{ah}, Fig. 6). The change in ampere turn rating is considerably greater with a nonventilated rotor than with a ventilated rotor. If the surface resistance is $^1/_2$ the value at 100 per cent rating for a nonventilated rotor, the ampere turns are increased 23 per cent. However, if the surface resistance is $^1/_2$ for the ventilated rotor, the ampere turns are increased 5 per cent. The resistance to radial heat flow to the gap is obviously much larger than the resistance to axial heat flow to the ventilating ducts.

Surface Losses (p_0, Fig. 6). In this case, also, the ampere turn rating decreases at a faster rate with a nonventilated rotor than with a ventilated rotor. Obviously surface losses must be limited to reasonably small values if affects on ampere turn rating are to be neglected.

Effect of Speed (Fig. 6). The peripheral speed affects the ventilation, and hence all surface dissipation rates are affected as well as the mean air rise through the rotor. Surface dissipation rates increase with the peripheral speed at the same rate as they increase with velocity. The ventilation loss also increases approximately as the cube of the peripheral speed, so that for large increases in peripheral speed, other factors being equal, the mean air rise would be the limiting factor with regard to increased ampere turn rating.

Thermal Resistance of Insulation (C_i, Fig. 7). The change in ampere turn rating as the insulation resistance is changed is greater with a ventilated

1. C_i. Over-all thermal resistivity of insulation for ventilated rotor 180 in. long
2. C_i. Same as curve 1 except rotor is not ventilated
3. C_i. Over-all thermal resistivity of insulation for nonventilated rotor 90 in. long
4. θ_0. Ambient temperature, degrees Centigrade

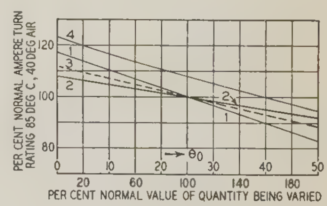


Fig. 7. Variation of ampere turn rating

rotor than with a nonventilated rotor. A ventilated rotor has a lower over-all thermal drop in the tooth than across the insulation compared to the nonventilated rotor. In large ventilated rotors, the probable gain in ampere turn rating which could be obtained by using aluminum oxide laminations as insulation in the space now used by the present type is about 10 per cent.

Ambient Air Temperature (θ_0, Fig. 7). The curve indicates that a change from 40 deg C ambient, the 100 per cent value, to 0 deg C has the effect of increasing the ampere turn rating 23 per cent. This assumes that the rotor temperature rise plus the ambient temperature has a constant value of 125 deg C.

Effect of End Winding Ventilation (Fig. 8). The longitudinal temperature distribution for various

schemes of ventilation indicates the advantages of good end winding ventilation. A typical example is shown in Fig. 8. The rise by resistance for curve 1 is 27 per cent greater than that for curve 3. Similarly, the rise by resistance for curve 2 is 22 per cent greater than for curve 3. For the same temperature rise, the high velocity blocking between coils gives an ampere turn rating increase of 11 per cent. The length of end winding is 20 per cent of the length of the coil. In many designs, especially those for 2-pole rotors, the end winding comprises 35 to 40 per cent of the total length of coil. For these cases, the effect of end winding ventilation on ampere turn rating is even more marked, amounting in some cases to an increase of 20 per cent.

Mean Air Temperature Rise (θ_a). All temperatures given above are rises above ambient air. An appreciable portion of this rise is due to the air temperature rise in the ventilating ducts and air gap. The mean air rise of the ventilating air through the rotor body is based upon the volume of ventilating air through the body and the losses which flow to the axial and radial vent ducts. There is another mean rise in the air gap due to the rotor surface and windage losses, and some losses from the tooth tips in the stator. Without going into detail, it should be stated that the mean air rise through the body of a ventilated rotor is 50 to 60 per cent of the total air rise through the machine, and the addition of the effects in the gap raises these values to 70 and 80 per cent. A more accurate estimate of the mean air rise θ_a depends upon the ventilation system, a knowledge of the volume of air going through the body of the rotor, and total air volume through the machine, as well as distribution of rotor losses between the radial vent ducts and the air gap.

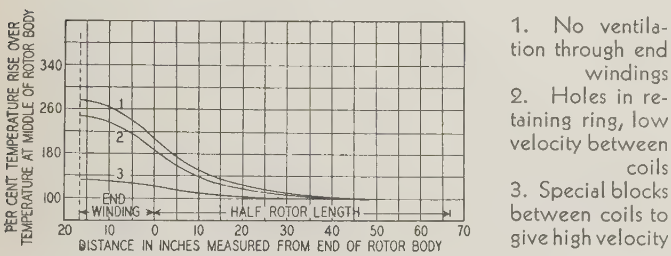


Fig. 8. Effect of end winding ventilation on temperature distribution

Summary

The application of the equivalent thermal circuits developed by C. R. Soderberg to the calculation of temperature rises in turbine generator rotors makes available a valuable tool for steady state temperature studies. The large number of variables can be handled in a relatively simple manner, which, together with the effect of end winding temperatures and longitudinal distribution, give a reasonably complete picture which can be applied with accuracy to all sizes and types of construction of turbine generator rotors.

It is also important to note that a reasonably accurate knowledge of the physical constants which depend upon the ventilation and thermal resistance of the various parts is necessary to make the application of the method truly valuable for all sizes and types of rotors.

The method being based upon sound fundamental assumptions, is applicable with some alteration to the slot region of any type of rotating electrical machine.

Appendix I—Symbols and Solutions of Thermal Circuits of Figs. 3 and 4

Meaning of Subscripts

a = air cooled surface
c = iron in core region
cu = copper
e = end windings
i = insulation
m = mean value
r = rotor body
t = iron in tooth region

In addition, the scheme of symbols is such that b refers to breadth or width, h refers to radial length, and l refers to axial length. Wherever possible, the various lengths are designated on Fig. 2.

Symbols (Alphabetically Arranged)

Above Surface of Division, Fig. 3

$b_{ah} = \dfrac{\pi d_r - Q_r b_s}{Q_r}$	cooled width of tooth in air gap. Pole surface uniformly distributed over tooth tips
b_{al}	$^1/_2$ perimeter of radial vent duct
b_{cu}	width of copper in slot
b_s	width of slot
b_{tm}	mean width of tooth
C_{ah}	mean surface resistance at air gap (degree [Centigrade] inches² per watt)
C_{al}	mean surface resistance at radial vent duct
$C_i = \rho_i t_i + \rho_a g_a$	surface resistance of slot insulation
$C_{ih} = \rho_i t_{ih}$	surface resistance of insulation above top strap
g_a	air space on one side of slot
h_{cu}	radial height of single copper conductor
h_i	see Fig. 2
h_s	depth of slot above surface of division
h_w	height of wedge at top of slot
l_t	center to center axial distance between radial vents (Fig. 2)
Q_r	number of rotor slots
Q_r'	number of rotor slots if original slot spacing was extended around entire periphery of rotor
t_i	thickness of slot insulation on one side
t_{ih}	thickness of insulation under wedge
t_{is}	thickness of insulation between conductors in slot
ρ_a	thermal resistivity of cooling medium (degrees Centigrade inches per watt)
ρ_i	thermal resistivity of insulation material
$\rho_{ih} = \rho_{is}\left(\dfrac{t_{is}}{h_{cu} + t_{is}}\right)$	equivalent thermal resistivity of conductors and insulation in radial direction
ρ_r	thermal resistivity of rotor tooth iron
ρ_w	thermal resistivity of rotor wedge
τ_s	center to center slot distance at air gap (slot pitch)

Below Surface of Division, Fig. 4 (Additional Symbols)

b_{aho}	cooling perimeter of axial vent duct at the bottom of the slot
b_c	mean width between axial vents in core region
b_0	width of axial vent
C_{aho}	mean surface resistance at axial vent duct

$C_{io} = \rho_{io} t_{io}$		mean surface resistance at bottom of slot
h_d		radial height of axial vent
t_{io}		thickness of insulation strip at bottom of slot

The solution outside of the surface of division combines the numbered resistances of Fig. 3 as follows:

$$
\begin{aligned}
C_{cul} &= h_i l_t \; [(6) + (7)] \\
C_h &= h_s l_t \; [(1) + (2)] \\
C_l &= h_s l_t \; [(3) + (4)]
\end{aligned} \tag{9}
$$

$$C_{tl} = \frac{Cl \cdot Ch}{C_l + C_h}$$

$$\mathrm{K} = \frac{h_s}{h_i} C_{cul} \div \left[\frac{h_s}{h_i} C_{cul} + C_l) + C_{tl}\right]$$

A dimensionless ratio which is a measure of the division of loss between the parallel paths. Then the temperature rise constants of eq 2 are

$$C_{cu} = \frac{\tau_s}{2h_s} \mathrm{K} \left[\frac{h_s}{h_i} C_l + C_{tl}\right]$$

$$C_t = \frac{\tau_s}{2h_s} \mathrm{K}\, C_{tl} \tag{10}$$

$$C_o = \frac{\tau_s}{b_{ah}} \frac{C_{tl}}{C_h} \mathrm{K}\, C_{ah}$$

At the surface of division (Fig. 1), the mean temperature of the tooth above ambient is

$$\theta_m = \theta_t \left(1 + \frac{h_s^2 \rho_r}{3 b_{tm} C_h}\right) \tag{11}$$

The distribution of copper losses in the thermal circuit of Fig. 3 is given by the values

$$
\begin{aligned}
m &= \mathrm{K} \left[1 - \frac{p_0}{p_{cu\theta}} \frac{2h_i}{b_{ah}} \frac{C_{tl}}{C_{cul}} \cdot \frac{C_{ah}}{C_h}\right] \\
n &= \frac{C_{tl}}{C_h} \left[1 - \frac{p_0}{p_{cu\theta} \cdot m} \cdot \frac{2h_s}{b_{ah}} \cdot \frac{C_{ah}}{C_l}\right]
\end{aligned} \tag{12}
$$

The quantities are dimensionless, m parts of the copper loss flow across the slot insulation to the tooth and $(1 - m)$ parts flow from the copper in a radial direction to the air gap. In the tooth, the m parts divide into n, and $(1 - n)$ parts to follow the parallel paths radially and axially, to gap and vent duct (see Fig. 3). The expressions simplify considerably when the surface losses are zero.

The solution of Fig. 4 inside of the surface of division introduces the following combination of the various numbered resistances:

$$
\begin{aligned}
C_{cul} &= h_i l_t \quad [(17) + (18)] \\
C_{hc} &= h_d l_t \quad [(8) + (9)] \\
C_{lc} &= h_d l_t \quad [(10) + (11)] \\
C_c &= \frac{C_{lc} C_{hc}}{C_{lc} + C_{hc}} \\
C_c^* &= \frac{[h_s l_t (12)] \left[\frac{h_s}{h_d} C_c\right]}{h_s l_t\,(12) + \frac{h_s}{h_d} C_c}
\end{aligned} \tag{13}
$$

The above quantities refer to the core region. For the tooth region, the following additional quantities are introduced.

$$
\begin{aligned}
C_l &= h_s l_t \; [(15) + (16)] \\
C_h^* &= C_c^* + [h_s l_t \, (13)] \\
C_{tl}^* &= \frac{C_l C_h^*}{C_l + C_h^*} \\
\mathrm{K} &= \frac{h_s}{h_i} C_{cul} \div \left[\frac{h_s}{h_i} (C_{cul} + C_l) + C_{tl}^*\right]
\end{aligned} \tag{14}
$$

Then the temperature rise constants are

$$
\begin{aligned}
C_{cu} &= \frac{\tau_s}{2h_s} \mathrm{K} \left(\frac{h_s}{h_i} C_l + C_{tl}^*\right) \\
C_{cut} &= \frac{\tau_s}{2h_s} \mathrm{K} C_{tl}^* \\
C_{cuc} &= \frac{\tau_s}{2h_d} \mathrm{K} C_c^* \frac{C_{tl}^*}{C_h^*}
\end{aligned} \tag{15}
$$

Appendix II—Temperature Rises in Rotor End Windings

A cross section of the coil in the ventilated portion of the end windings is shown in Fig. 9. Bare copper is exposed to the cooling medium with the exception of that portion covered by the insulating

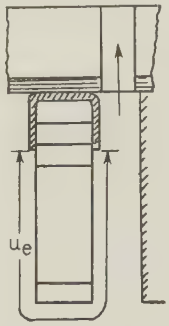


Fig. 9. Ventilated portion of end winding

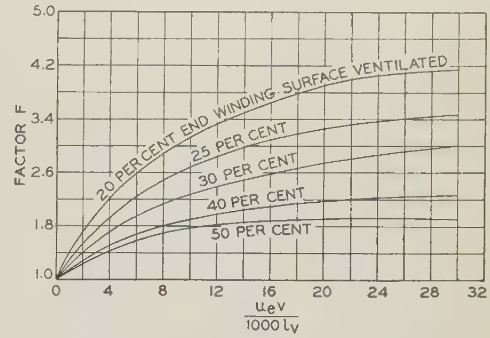


Fig. 10. Factor F for calculation of end winding temperatures

channel under the rotor retaining ring. The heat flow through the channel and retaining ring insulation is not considered because of its small magnitude. The following additional symbols are required:

u_e	cooled perimeter of one coil (Fig. 9)
l_v	cooled length of one coil on one side corresponding to one ventilating hole in retaining ring or one block between coils to give high velocity over coil surface
v	velocity of cooling medium over cooled portion of coil
C_{ae}	mean surface resistance from bare copper to cooling medium
p_{cue}	copper loss in watts per square inch. This is equivalent to P_{cue} divided by $\tau_s l_t/2$, where P_{cue} is total loss generated in the coil length $l_t/2$

Defined in this manner, p_{cu} used in the calculation of body temperatures is equivalent to p_{cue}.

The temperature rise constant for the end windings is given by

$$C_{cue} = F \frac{\tau_s}{u_e} C_{ae}$$

F is taken from Fig. 10, and allows for the heat flow from the non-ventilated portions of the end winding with various percentages of the total end winding coil surface ventilated. The use of the factor F considerably shortens the work of calculating the end winding temperatures.

The mean temperature rise of the end winding, assuming no heat interchange with the rotor body, is

$$\theta_{cue} = \frac{310}{310 - p_{cue} C_{cue}} \left[\theta_{ae} + p_{cue} C_{cue} \left(\frac{235 + \theta_0}{310}\right)\right] \tag{17}$$

in which correction for changes in resistance is allowed for and the copper loss p_{cue} is evaluated at 75 deg C. θ_{ae} is the mean rise of the cooling medium through the end windings.

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A New Timer for Resistance Welding

A new type of timer and controller for use in the field of resistance welding of thin alloy sheets of brass, aluminum, stainless steel, and kindred metals where a very high current is applied for a very short interval of time is described in this paper. In this new timer, the "ignitron" type of tube is applied for obtaining precise control of the welding current. Controls for intermittent duty, high speed automatic duty, and heavy duty seam welding are described.

By
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SPOT or resistance welding as commonly performed employs a transformer to reduce the commercial a-c voltage to a few volts and to produce an inversely high current suitable to fuse 2 metal parts together. This low voltage is applied to electrodes which are in the form of studs or wheels, exerting pressure on each of the 2 parts to be joined. In order that a weld be satisfactory both the magnitude of the current and its duration must be controlled accurately. Where the time is short and the current correspondingly high, the weld is concentrated in a small area at the contact surface, and as a result the weld is weak under shearing stress. If the time is long and the current low the weld covers a greater area at the contact surfaces and in addition penetrates through a greater volume of metal causing burning and severe warping or deformation at the surface. Obviously a compromise between these conditions is desirable, both the time and magnitude of current varying with the physical and chemical properties of the pieces to be joined.

Electromechanical contactors have been used to establish and interrupt the current in the primary of the welding transformer at a time rate suitable to proper fusion. When spots are made in rapid succession the duty on the mechanical switch is severe. Burning of the arcing tips and mechanical wear result in high maintenance and inconsistencies between successive spots. More serious is the inaccuracy of the mechanical switch, particularly where thin stock is to be welded and this stock is an alloy carefully processed for certain physical and chemical properties. The time of welding is of the order of a few half cycles and one additional half cycle constitutes a high percentage of increased heat in the weld. Also, for consistent results, the transformer must be energized at the correct power factor angle or definite point on the voltage wave to prevent high magnetizing surges; these transients increase or decrease the heat in the weld as the time of fire is varied from that corresponding to zero current.

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted May 8, 1934; released for publication July 23, 1934. *Not published in pamphlet form.*

Theory of Operation

The "ignitron" welding timer performs the function of a rapid action single-pole single-throw switch connected in series with the power source and the primary of the welding machine transformer. The function of the vital parts of the timer is illustrated in Fig. 1. Power current is carried and interrupted by 2 "ignitron[1]" tubes. These tubes are connected in parallel inverse relation, the combination serving to pass alternating current, and are placed directly in series with the power source and welding transformer primary. These tubes have been described in other papers (see "A New Method for Initiating the Cathode of an Arc" by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., v. 52, 1933, p. 693–8; and "The Ignitron—A New Controlled Rectifier" by D. D. Knowles, *electronics*, v. 6, 1933, p. 164–6) so that only their important characteristics are reviewed here.

The ignitron tubes are of the mercury pool cathode type and have essentially the same characteristics as conventional pool type rectifiers; they do not have the crest current limitations of the hot cathode type. An ignition electrode or crystal dips into the mercury pool. A small ignition current fires the tube for each desired loop of welding current. Once a half-cycle of current is initiated in either ignitron tube it will continue to the end of the loop, at which time the arc is automatically extinguished. Contactors or relays are not relied upon, either to interrupt the power current or to control the duration of the weld. Timing is entirely

1. "Ignitron" is a trade name of the Westinghouse Electric and Manufacturing Company.

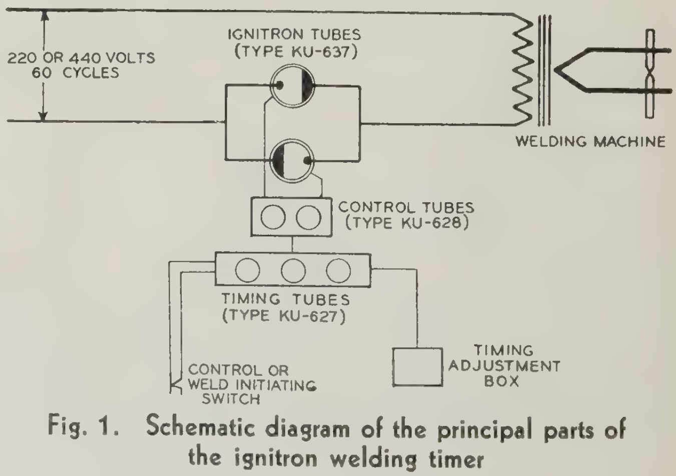


Fig. 1. Schematic diagram of the principal parts of the ignitron welding timer

electronically controlled. In operation, each closure of the weld initiating contacts will measure out a predetermined number of cycles of welding current. These contacts may be either manual or machine operated. Welding current always begins at a predetermined point on the voltage wave regardless of time of closure of the initiating switch.

A more complete schematic diagram is shown in Fig. 2. Tubes T, T_2, and T_3 are the timing tubes. T_4 and T_5 are the control tubes which control the ignition electrodes in the ignitron tubes A and B. Both the timing and control tubes are the mercury vapor arc discharge type. They are the hot cathode or filament type and are grid controlled. To block these tubes, negative potential is applied to the grid. To cause breakdown, zero or positive potential is applied. Tube T is the initiating tube and is supplied from an a-c source in synchronism with the power supply to the welder. The a-c grid cathode voltage may be varied in phase by means of capacitor C_1 and variable resistor R_6. Thus when the grid becomes positive the tube breaks down at a controllable or preset point in the positive half cycle of anode voltage. At breakdown of T a surge voltage is generated in the secondary of transformer 1. Thus tube T permits the operator to initiate welding current always at the natural zero point of current on the voltage wave, or at the correct factor power angle.

Tube T_2 may be termed the starting tube. After closure of the weld initiating switch and at the next grid voltage surge from tube T through transformer 1 tube T_2 will break down and start the flow of welding current. Up to this point T_2 has been blocked off by negative grid source S_2. After breakdown of T_2 positive or energizing grid bias is applied to the grids of T_4 and T_5 from the voltage drop across resistor R_2. Breakdown of T_4 and T_5

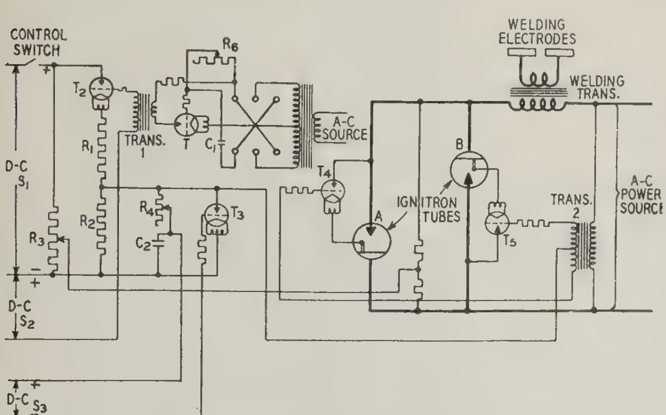


Fig. 2. A more complete schematic diagram of the ignitron welding timer

causes ignition of the ignitron power tubes and the consequent flow of welding current. It can be seen by inspection of the circuit that prior to breakdown of the start tube T_2, negative or holding potential is applied continuously to the grids of T_4 and T_5. After breakdown of T_2 this potential is shifted to positive. The function of transformer 2 and potentiometer is to nullify the a-c potential

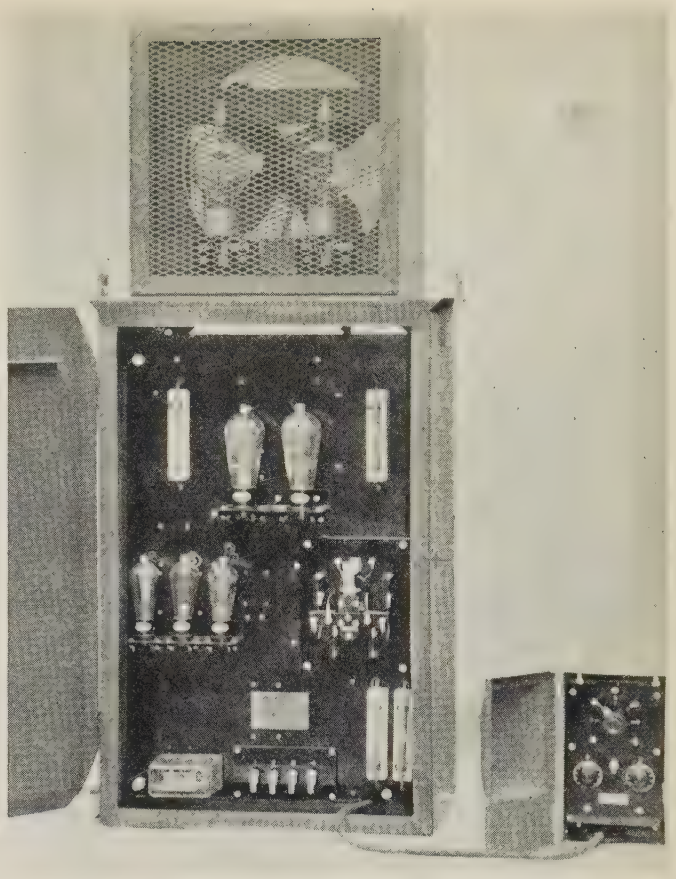


Fig. 3. Assembly of the ignitron welding timer with covers open

which would otherwise exist on the grids of T_4 and T_5 due to their circuit locations. When the current from the line through the control tube and ignition electrode has reached sufficient magnitude, the main ignition anode picks up the load and shorts out the control tube thus cutting off further flow of igniting current which is no longer necessary.

The foregoing sequence shows how welding current is initiated. Tube T_3 may be termed the "stop" tube. It normally has a negative holding source S_3 applied to its grid. After breakdown of the start tube T_2, timing capacitor C_2 is charged through a variable resistor R_4. After a definite time, controllable by C_2 and R_4, capacitor C_2 will become sufficiently charged to offset negative bias S_3 on the grid of "stop" tube T_3 and it breaks down. At breakdown of T_3 resistor R_2 is in effect shorted out and the bias voltage on the control tubes again becomes negative, thereby preventing further flow of welding current. It is only necessary that cut-off occur during the last desired half cycle of welding current, as once ignited the ignitron tube will pass current to the end of the half cycle. Between welds it is, of course, necessary to discharge capacitor C_2 and to open the control switch thereby extinguishing tubes T_2 and T_3.

Description and Rating

The ignitron welding timer consists of a panel assembly mounted in a rugged steel cabinet, and is

shown in Fig. 3. The ignitron power tubes are mounted in a metal-screened fan-ventilated housing, bolted to the top of the main control cabinet. On the upper portion of the panel and centrally located are the 2 grid glow tubes which control the ignition electrodes of the power tubes. In the mid-section of the panel and on the left-hand side are located the 3 timing tubes. On the right-hand side of the panel is an initiating relay. In the lower left-hand corner is a time delay relay to protect the cathodes of the timing and control tubes during their heating. Heating time is 45 sec. Terminal connections are at the bottom center of the panel and protective fuses for the auxilary control circuit are located in the lower right-hand corner.

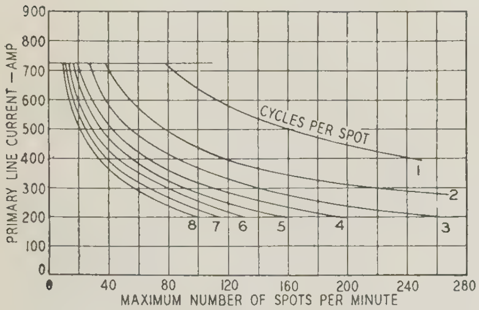


Fig. 4. Curves of current capacity of the 220–440-volt 60-cycle fan-cooled welding timer using ignitron tubes, type KU-637

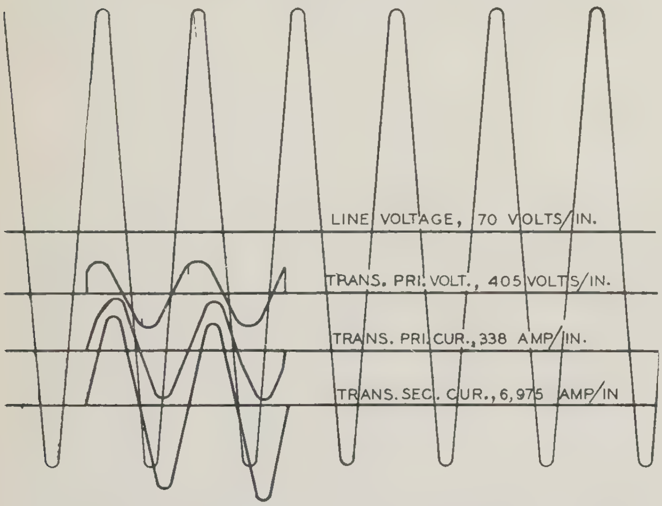


Fig. 5. Reproduction of an oscillogram showing performance of the timer when welding stainless steel

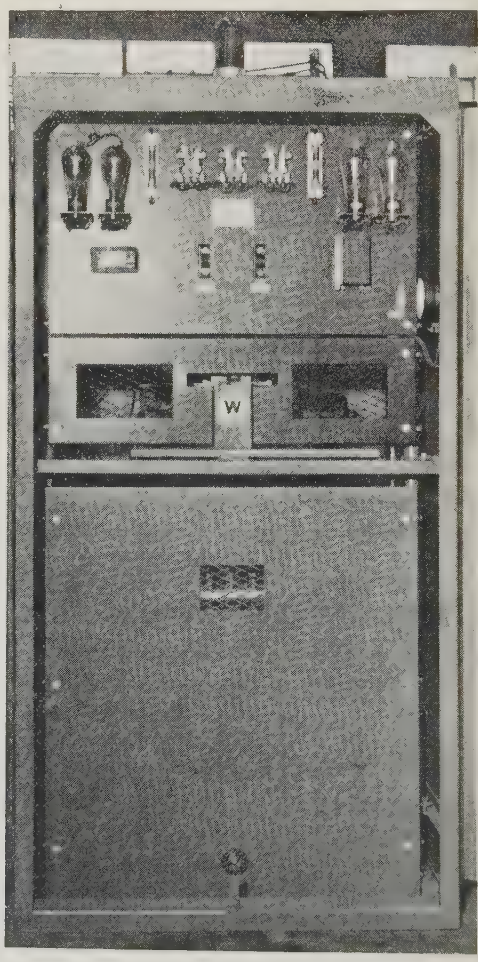
In the small box shown at the right of the main control cabinet are the timing resistors and capacitors. This unit is carefully calibrated and gives accurate control of 1 to 14 cycles. Combinations of tap switch and left-hand dial give the desired number of cycles. The right-hand dial controls the point on the voltage wave where the weld is initiated. This control box is usually mounted in a convenient position near the operator. The curves in Fig. 4 illustrate the rating or power that can be handled. Primary line current in root mean square amperes during weld is plotted against maximum number of spots per minute for several values of cycles per spot. The curve shows that 710 amp at 440 volts, or 312.4 kva, may be handled at a speed of 80 spots per minute with one cycle per spot. The same kilovoltampere load with 5 cycles per spot has a maximum duty cycle of 30 spots per minute. In Fig. 5 is a reproduction of an oscillogram showing performance of the timer when welding stainless steel in 2 cycles of current. Note that the trace of transformer primary voltage indicates the weld was initiated at about 45 deg on the line voltage wave.

Heavy Duty Seam Welding

The foregoing controller is suitable for light duty intermittent spotting. For heavy-duty gas-tight seam welding another form of controller is essential. In this type of welding, spots are made in rapid succession on a roller type welder with automatic timing such that a 50 per cent overlap of adjacent spots is obtained.

The ignitron seam welding timer consists of 3 major unit assemblies: (1) A synchronously driven "photo-timer"; (2) a control tube panel assembly; and (3) an ignitron power tube assembly. These 3 unit assemblies are mounted in a suitable steel cabinet as illustrated in Fig. 6. The synchronously driven photo-timer unit is mounted on the central compartment shelf. Directly above this shelf is the control tube panel assembly. The lower section of the cabinet contains the ignitron power tube assembly. The action of this timer may be likened to the ignition system on the average automobile.

Fig. 6. The ignitron seam welding timer with covers open



The photo-timer corresponds to the distributor, the control panel to the ignition coil, and the ignitron tube assembly to the cylinders, the latter having ignition electrodes which correspond to spark plugs in the cylinders of the automobile.

Similar to the spot welder control just described this timer performs the function of a rapid action single-pole single-throw switch connected directly in series with the power source and the primary of the welding machine transformer. Power current is carried and interrupted by 2 ignitron power tubes. These tubes are connected in parallel and inversely to one another, the combination serving to pass alternating current. The ignitron tubes are controlled by control tubes located on the control panel, and these control tubes are actuated by the output of the photo-timer.

Photo-Timer

The purpose of the motor driven photo-timer is to control both the number of cycles of current per weld and the number of cycles interval between welds. This is accomplished by periodic interruption of a narrow light beam by teeth in a revolving disk. Adjustments permit variation of weld duration and weld spacing. The photo-timer therefore consists essentially of a synchronous motor driving a revolving disk, a light source, the necessary lenses, apertures, photo-electric tubes, amplifier tubes, and auxiliaries, and is shown in Fig. 7.

The timing disk of the photo-electric timer contains 120 slots around the periphery at intervals corresponding to each half cycle. The slots for which welding current is desired are left unmasked by a specially cut fish-paper disk clamped over the slotted timing disk. It will be seen that various combinations of weld duration and weld spacing may be obtained readily. An adjustment allows positioning of the light beam with respect to rotational position of the slotted disk. Since the unmasked slots correspond to welding current, it is apparent that the starting point of each current loop may be varied to any desired point on the voltage wave by the adjustment screws which shift the light beam with respect to the timing disk. In other words, current zero of the loop is removed from voltage zero by an electrical angle equal to the load power factor angle. For convenience in setting this adjustment a zero center d-c meter is connected to a shunt in the a-c load circuit. This meter indicates the presence of unequal current loops by registration of any d-c component in welding current.

Circuit Operation

A schematic wiring diagram is shown in Fig. 8. When an open slot in the revolving timing disk allows light to strike the cathode of the photo-electric tube, current flows through the tube and resistor R_1. The first stage amplifier thus receives a more positive bias and passes increased plate current through resistor R_2. Through coupling condenser C, the second stage tube has its grid forced negative, thus decreasing the plate current of the second stage tube. The output transformer primary winding is in this circuit and hence the secondary winding receives voltage corresponding in duration to the slot width in the timing disk. A weld initiating

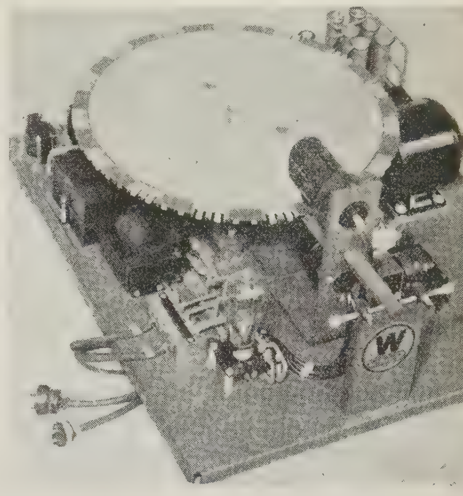


Fig. 7. The photo-timer of the ignitron seam welding timer

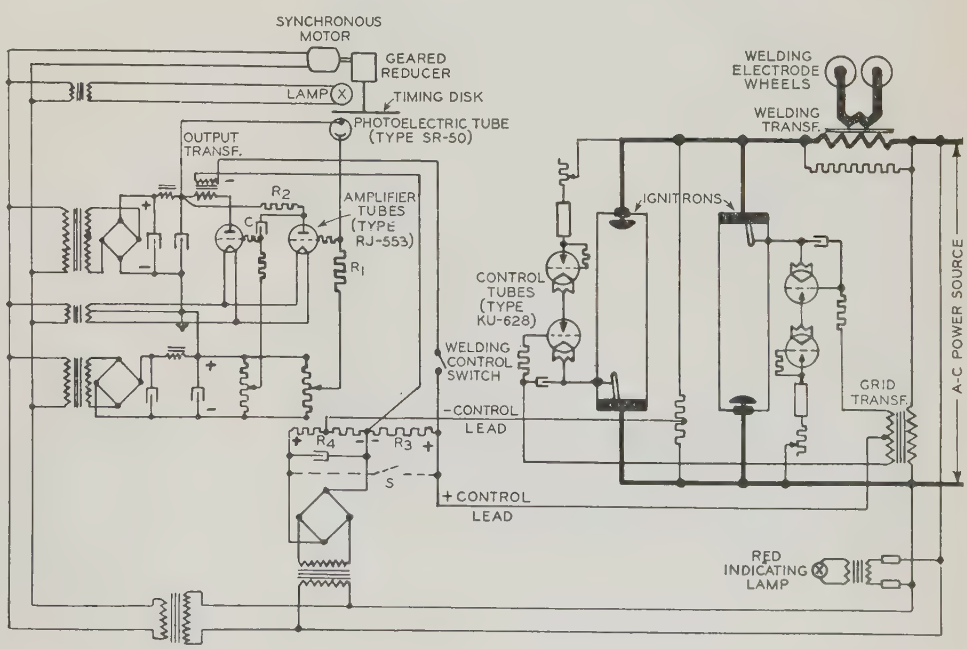


Fig. 8. Schematic wiring diagram of the seam welding timer

potential thus appears across resistor R_3 of the polarity shown.

The output of the photo-timer produces a positive potential across the control leads by overcoming the constant negative potential normally across resistor R_4. The resultant positive d-c bias is applied to the control tube grids through the grid transformer secondary. Both control tubes are now energized in so far as the grids are concerned and ignition current instantly flows through the 2 control tubes of the ignitron, which at the moment has positive anode potential. Inverse anode potential on the remaining tube prevents, as yet, its operation, which must wait upon the next succeeding current zero. Once either ignitron is fired, its low arc drop voltage prevents further ignition current to flow through the 2 series connected control tubes.

Control Tube Panel Assembly

The control tube panel assembly is shown in the upper portion of Fig. 6. Mounted at the top of the panel are 2 pairs of control tubes of the grid glow type. Their function is to control the welding current through control of the ignition or starting current of the ignitron power tubes. The grids of these control tubes are actuated by the output of the photo-timer. Each pair of tubes is connected in series and forms a circuit between the anode and ignition electrode of each ignitron power tube. In the upper center are 3 auxiliary relays used to protect against thermal overload, water failure, etc., and interlocked with the manually operated switches directly below so that complete protection and safety are provided even in the hands of an unskilled operator.

Ignitron Power Tube Assembly

This assembly consists essentially of 2 ignitron power tubes, a water cooling system, and a vacuum pumping system. In Fig. 9 is a detailed view of this assembly. The ignitrons are of the all-metal steel-tank type with graphite anodes. A system of water jackets on the tube and small anode cooling radiator fins at the top of the tube remove the heat generated by the arc. Their circuit relations are such that the cathodes are 440 volts apart and it is necessary to provide insulation in feeding from a common water system. Directly in front of the tubes are located insulating hose reels conveying water to the tube jackets. Near the top of the assembly are 2 hand-wheels controlling valves which close off the tubes from the pumping system when the unit is shut down for an extended period. These valves connect to a manifolding which is exhausted by a conventional jet type 3-stage mercury pump. This mercury pump discharges into an interstage reservoir whose pressure is maintained at or below 6 mm by a rotary oil pump. It is necessary that the oil pump run only occasionally as the volume of gas pumped is very small. Automatic starting and stopping of the oil pump is controlled by a glass mercury manometer switch making contact at definite pressures. To prevent air leaking back through the oil pump, an automatic valve is placed between the oil pump and interstage reservoir. Suitable bus bar and power cable connections are provided at the rear of the unit. Visible water discharge nozzles are shown at the front of the unit together with master hand valve and regulating key valves.

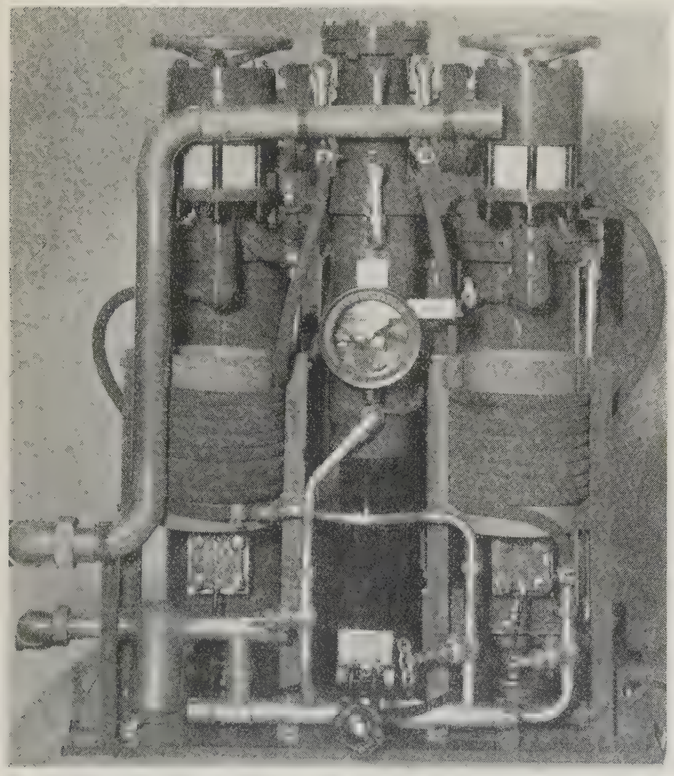


Fig. 9. Assembly of the ignitron power tubes of the seam welding timer

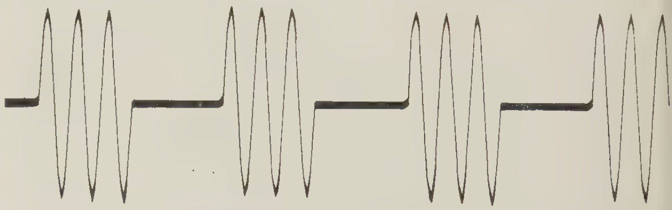


Fig. 10. Reproduction of oscillogram of current supplied by the seam welding timer

Rating and Performance

The ignitron seam welder timer is rated 350–700 kva at 220–440 volts on a 25 per cent duty cycle. The thermal rating of each ignitron power tube is 200 amp average. A peak current rating of 2,250 amp has been tentatively used pending further investigation and study. On recent tests these tubes were successful in handling a crest of 4,800 amp at 440 volts. An oscillogram of the current handled by the controller is reproduced in Fig. 10. The trace illustrates 3 cycles of current and a space of 3 cycles with the timer set at the natural zero of the current.

Wide Band Transmission Over Coaxial Lines

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In this paper systems are described whereby frequency band widths of the order of 1,000 kc or more may be transmitted for long distances over coaxial lines and utilized for purposes of multiplex telephony or television. A coaxial line is a metal tube surrounding a central conductor and separated from it by insulating supports.

IT appears from recent development work that under some conditions it will be economically advantageous to make use of considerably wider frequency ranges for telephone and telegraph transmission than are now in use[1,2] or than are covered in the recent paper on carrier in cable.[3] Furthermore, the possibilities of television have come into active consideration and it is realized that a band of the order of 1,000 kc or more in width would be essential for television of reasonably high definition if that art were to come into practical use.[4,5]

This paper describes certain apparatus and structures which have been developed to employ such wide frequency ranges. The future commercial application of these systems will depend upon a great many factors, including the demand for additional large groups of communication facilities or of facilities for television. Their practical introduction is, therefore, not immediately contemplated and, in any event, will necessarily be a very gradual process.

Types of High Frequency Circuits

The existing types of wire circuits can be worked to frequencies of tens of thousands of cycles, as is evidenced by the widespread application of carrier systems to the open wire telephone plant and by the development of carrier systems for telephone cable circuits.[2,3] Further development may lead to the operation of still higher frequencies over the existing types of plant. However, for protection against external interference these circuits rely upon balance, and as the frequency band is widened, it becomes more and more difficult to maintain a sufficiently high degree of balance. The balance requirements may be made less severe by using an individual shield around each circuit, and with sufficient shielding balance may be entirely dispensed with.

A form of circuit which differs from existing types in that it is unbalanced (one of the conductors being grounded), is the coaxial or concentric circuit. This consists essentially of an outer conducting tube which envelops a centrally disposed conductor. The high-frequency transmission circuit is formed between the inner surface of the outer conductor and the outer surface of the inner conductor. Unduly large losses at the higher frequencies are prevented by the nature of the construction, the inner conductor being so supported within the tube that the intervening dielectric is largely gaseous, the separation between the conductors being substantial, and the outer conductor presenting a relatively large surface. By virtue of skin effect, the outer tube serves both as a conductor and a shield, the desired currents concentrating on its inner surface and the undesired interfering currents on the outer surface. Thus, the same skin effect which increases the losses within the conductors provides the shielding which protects the transmission path from outside influences, this protection being more effective the higher the frequency.

The system which this paper outlines has been based primarily upon the use of the coaxial line. The repeater and terminal apparatus described, however, are generally applicable to any type of line, either balanced or unbalanced, which is capable of transmitting the frequency range desired.

The Coaxial System

A general picture of the type of wide band transmission system which is to be discussed is briefly as follows: A coaxial line about 0.5 in. in outside diameter may be used to transmit a frequency band of about 1,000 kc, with repeaters capable of handling the entire band placed at intervals of about 10 miles. Terminal apparatus may be provided which will enable this band either to be subdivided into more than 200 telephone circuits or to be used *en bloc* for television.

Such a wide band system is illustrated in Fig. 1. It is shown to comprise several portions, namely, the line sections, the repeaters, and the terminal apparatus, the latter being indicated in this case as for multiplex telephony. Two-way operation is secured by using 2 lines, one for either direction. It would be possible, however, to divide the frequency band and use different parts for transmission in opposite directions.

A form of flexible line which has been found con-

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1. For all numbered references, see list at end of paper.

venient in the experimental work is illustrated in Fig. 2 and will be described more fully subsequently. Such a coaxial line can be constructed to have the same degree of mechanical flexibility as the familiar telephone cable. While this line has a relatively high loss at high frequencies, the transmission path is particularly well adapted to the frequent application of repeaters, since the shielding permits the transmission currents to fall to low power levels at the high frequencies.

Of no little importance also is the fact that the attenuation-frequency characteristic is smooth throughout the entire band and obeys a simple law of change with temperature. (This is due to the fact that the dielectric is largely gaseous and that insulation material of good dielectric properties is employed.) This smooth relation is extremely helpful in the provision of means in the repeaters for automatically compensating for the variations which occur in the line attenuation with changes of temperature. This type of system is featured by large transmission losses which are offset by large amplification, and it is necessary that the 2 effects match each other accurately at all times throughout the frequency range.

It will be evident that the repeater is of outstanding importance in this type of system, for it must not only transmit the wide band of frequencies with a transmission characteristic inverse to that of the line, with automatic regulation to care for temperature changes, but must also have sufficient freedom from inter-modulation effects to permit the use of large numbers of repeaters in tandem without objectionable interference. Fortunately, recent advances in repeater technique have made this result possible, as will be appreciated from the subsequent description.

An interesting characteristic of this type of system is the way in which the width of the transmitted band is controlled by the repeater spacing and line size, as follows:

1. For a given size of conductor and given length of line, the band width increases nearly as the square of the number of the repeater points. Thus, for a coaxial circuit with about 0.3-in. inner diameter of outer conductor, a 20-mile repeater spacing will enable a band up to about 250 kc to be transmitted, a 10-mile spacing will increase the band to about 1,000 kc, and a 5-mile spacing to about 4,000 kc.

2. For a given repeater spacing, the band width increases approximately as the square of the conductor diameter. Thus, whereas a tube of 0.3-in. inner diameter will transmit a band of about 1,000 kc, 0.6-in. diameter will transmit about 4,000 kc, while a diameter corresponding to a full sized telephone cable might transmit something of the order of 50,000 kc, depending upon the dielectric employed and upon the ability to provide suitable repeaters.

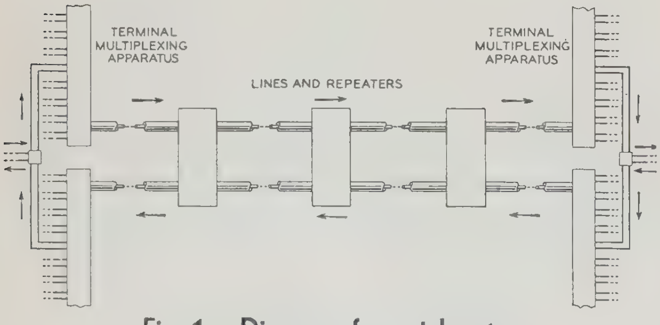


Fig. 1. Diagram of coaxial system

Earlier Work

It may be of interest to note that as a structure, the coaxial form of line is old—in fact, classical. During the latter half of the last century it was the object of theoretical study, in respect to skin effect and other problems, by some of the most prominent mathematical physicists of the time. Reference to some of this work is made in a paper by Schelkunoff, dealing with the theory of the coaxial circuit.[6]

On the practical side, it is found on looking back over the art that the coaxial form of line structure has been used in 2 rather widely different applications: First, as a long line for the transmission of low frequencies, examples of which are usage for submarine cables[7,8] and for power distribution purposes, and second as a short-distance high-frequency line serving as an antenna lead-in.[9,10]

The coaxial conductor system herein described may be regarded as an extension of these earlier applications to the long distance transmission of a very wide range of frequencies suitable for multiplex telephony or television.[11] Although dealing with radio frequencies, this system represents an extreme departure from radio systems in that a relatively broad band of waves is transmitted, this band being confined to a small physical channel which is shielded from outside disturbances. The system, in effect, comprehends a frequency spectrum of its own and

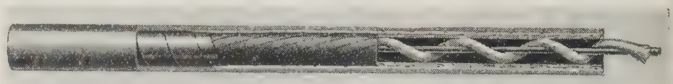


Fig. 2. Small flexible coaxial structure

shuts it off from its surroundings so that it may be used again and again in different systems without interference.

This new type of facility has not yet been commercially applied, and is, in fact, still in the development stage. Sufficient progress has already been made, however, to give reasonable assurance of a satisfactory solution of the technical problems involved. This progress is outlined below under 3 general headings: (1) the coaxial line and its transmission properties, (2) the wide band repeaters, and (3) the terminal apparatus.

The Coaxial Line

An Experimental Verification

One of the first steps taken in the present development was in the nature of an experimental check of the coaxial conductor line, designed primarily to determine whether the desirable transmission properties which had been disclosed by a theoretical study could be fully realized under practical conditions. For this purpose a length of coaxial structure capable of accurate computation was installed near Phoenix-

ville, Pa. The diagram of Fig. 3 shows a sketch of the structure used and gives its dimensions. It comprised a copper tube of 2.5-in. outside diameter, within which was mounted a smaller tube which, in turn, contained a small copper wire. Two coaxial circuits of different sizes were thus made available, one between the outer and the inner tubes, and the other between the inner tube and the central wire. The installation comprised 2 2,600-ft lengths of this structure.

The diameters of these coaxial conductors were so chosen as to obtain for each of the 2 transmission paths a diameter ratio which approximates the optimum value, as discussed later. The conductors were separated by small insulators of isolantite. The rigid construction and the substantial clearances between conductors made it possible to space the insulators at fairly wide intervals, so that the dielectric between conductors was almost entirely air.

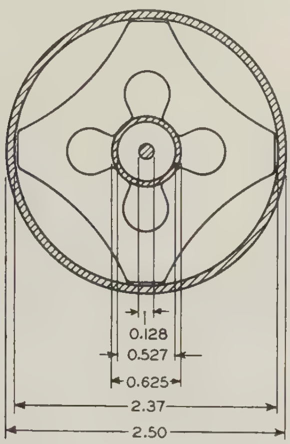
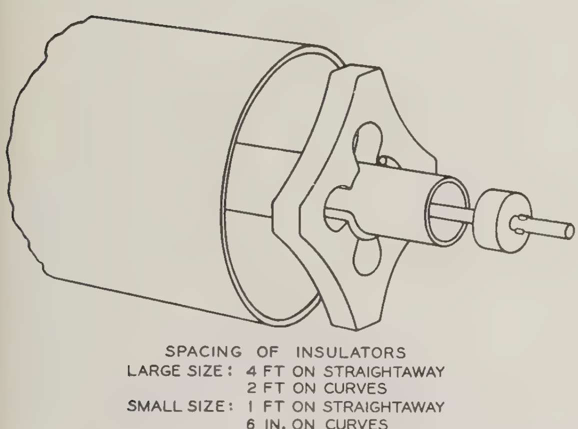


Fig. 3. Structure used in Phoenixville installation



The outer conductor was made gastight, and the structure was dried out by circulating dry nitrogen gas through it. The 2 triple conductor lines were suspended on wooden fixtures and the ends brought into a test house, as shown in Fig. 4.

The attenuation was measured by different methods over the frequency range from about 100 kc to 10,000 kc. Investigation showed that the departures from ideal construction occasioned by the joints, the lack of perfect concentricity, etc., had remarkably little effect upon the attenuation. In order to study the effect of eccentricity upon the attenuation, tests were made in which this effect was much exaggerated, and the results substantiated theoretical predictions. The impedance of the circuits was measured over the same range as the attenuation. A few measurements on a short length were made at frequencies as high as 20,000 kc.

Fig. 4. Phoenixville installation showing conductors entering test house

Measurements were secured of the shielding effect of the outer conductor of the coaxial circuit up to frequencies in the order of 100 to 150 kc, the results agreeing closely with the theoretical values. Above these frequencies, even with interfering sources much more powerful than would be encountered in practice, the induced currents dropped below the level of the noise due to thermal agitation of electricity in the conductors (resistance noise) and could not be measured.

The preliminary tests at Phoenixville, therefore, demonstrated that a practical coaxial circuit, with its inevitable mechanical departures from the ideal, showed transmission properties substantially in agreement with the theoretical predictions.

Small Flexible Structures

Development work on wide band amplifiers, as discussed later, indicated the practicability of employing repeaters at fairly close intervals. This pointed toward the desirability of using sizes of coaxial circuit somewhat smaller than the smaller of those used in the preliminary experiments, and having correspondingly greater attenuation. Furthermore, it was desired to secure flexible structures which could be handled on reels after the fashion of ordinary cable. Accordingly, several types of flexible construction, ranging in outer diameter from about 0.3 in. to 0.6 in., have been experimented with. Structures were desired which would be mechanically and electrically satisfactory, and which could be manufactured economically, preferably with a continuous process of fabrication.

One type of small flexible structure which has been developed is shown in Fig. 2. The outer conductor is formed of overlapping copper strips held in place with a binding of iron or brass tape. The insulation consists of a cotton string wound spirally around the inner conductor, which is a solid copper wire. This structure has been made in several sizes of the order of 0.5-in. diameter or less. When it is to be used as an individual cable, the outer conductor is surrounded by a lead sheath, as shown, to prevent the

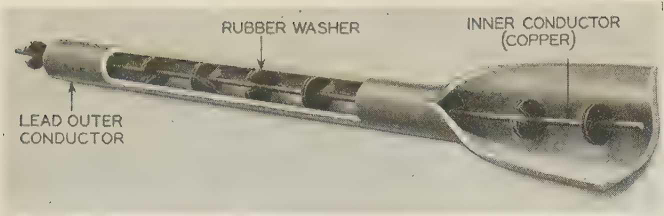


Fig. 5. Photograph of coaxial structure with lead outer conductor and rubber disk insulators

entrance of moisture. One or more of the copper tape structures without individual lead sheath may be placed with balanced pairs inside a common cable sheath.

Another flexible structure is shown in Fig. 5. The outer conductor in this case is a lead sheath which directly surrounds the inner conductor with its insulation. Since lead is a poorer conductor than copper, it is necessary to use a somewhat larger diameter with this construction in order to obtain the same transmission efficiency. Lead is also inferior to copper in its shielding properties and to obtain the same degree of shielding the lead tube of Fig. 5 must be made correspondingly thicker than is necessary for a copper tube.

The insulation used in the structure shown in Fig. 5 consists of hard rubber disks spaced at intervals along the inner wire. Cotton string or rubber disk insulation may be used with either form of outer tube. The hard rubber gives somewhat lower attenuation, particularly at the higher frequencies.

Another simple form of structure employs commercial copper tubing into which the inner wire with its insulation is pulled. Although this form does not lend itself readily to a continuous manufacturing process, it may be advantageous in some cases.

Transmission Characteristics—Attenuation

At high frequencies the attenuation of the coaxial circuit is given closely by the well-known formula:

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} \qquad (1)$$

where R, L, C and G are the 4 so-called "primary constants" of the line, namely, the resistance, inductance, capacitance, and conductance per unit of length. The first term of eq 1 represents the losses in the conductors, while the second term represents those in the dielectric.

When the dielectric losses are small, the attenuation of a coaxial circuit increases, due to skin effect in the conductors, about in accordance with the square root of the frequency. With a fixed diameter ratio, the attenuation varies inversely with the diameter of the circuit. By combining these relations there are obtained the laws of variation of band width in accordance with the repeater spacing and the size of circuit, as stated previously.

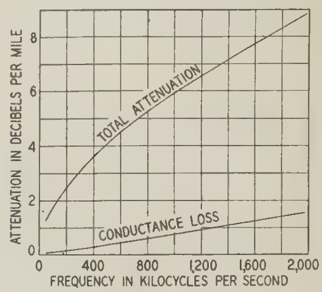
The attenuation-frequency characteristic of the flexible structure illustrated in Fig. 2, with about 0.3-in. diameter, is given in Fig. 6. The figure shows also that the conductance loss due to the insulation is a small part of the total.

It is interesting to compare the curves of the transmission characteristics of the coaxial circuit with those of other types of circuits. The diagram of Fig. 7 shows the high-frequency attenuation of 2 sizes of coaxial circuit using copper tube outer conductors, of 0.3-in. and 2.5-in. inner diameter, and that of cable and open wire pairs in the same frequency range.

Effect of Eccentricity

The small effect of lack of perfect coaxiality upon the attenuation of a coaxial circuit is illustrated by the curve of Fig. 8, which shows attenuation ratios plotted as a function of eccentricity, assuming a fixed ratio of conductor diameters and substantially air insulation.

Fig 6. Attenuation of small flexible coaxial structure shown in Fig. 2



Temperature Coefficient

With a coaxial circuit, as with other types of circuits, the temperature coefficient of resistance decreases as the frequency is increased, due to the action of skin effect, and approaches a value of $^1/_2$ the d-c temperature coefficient.[12] Thus, for conductors of copper the a-c coefficient at high frequencies is approximately 0.002 per degree Centigrade. When the dielectric losses are small, the temperature coefficient of attenuation at high frequencies is the same as the temperature coefficient of resistance.

Diameter Ratio

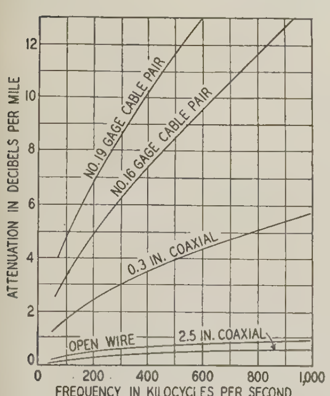
An interesting condition exists with regard to the relative sizes of the 2 conductors. For a given size of outer conductor there is a unique ratio of inner diameter of outer conductor to outer diameter of inner conductor which gives a minimum attenuation. At high frequencies, this optimum ratio of diameters (or radii) is practically independent of frequency. When the conductivity is the same for both conductors, and either the dielectric losses are small or the insulation is distributed so that the dielectric flux follows radial lines, the value of the optimum diameter ratio is approximately 3.6. When the outer and inner conductors do not have the same conductivity, the optimum diameter ratio differs from this value. For a lead outer conductor and copper inner conductor, for example, the ratio should be about 5.3.

Stranding

Inasmuch as the resistance of the inner conductor contributes a large part of the high frequency attenuation of a coaxial circuit, it is natural to consider the possibility of reducing this resistance by employing a conductor composed of insulated strands suitably twisted or interwoven.[13] Experiments along this line showed that this method is impractical at frequencies above about 500 kc, owing to the fineness of stranding required.

Characteristic Impedance

The high-frequency characteristic impedance of a coaxial circuit varies inversely with the square root of the effective dielectric constant, i. e., the ratio of the actual capacitance to the capacitance that would be obtained with air insulation. The impedance of a circuit having a given dielectric constant depends merely upon the ratio of conductor diameters and not upon the absolute dimensions. For a diameter ratio of 3.6, the impedance of a coaxial circuit with gaseous dielectric is about 75 ohms.



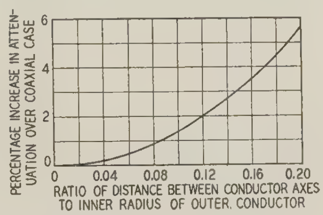


Fig. 8 (above). Increase in attenuation of coaxial circuit due to eccentricity

Fig. 7 (left). Attenuation frequency characteristics of coaxial and other circuits

Velocity of Propagation

For a coaxial circuit with substantially gaseous insulation, the velocity of propagation at high frequencies approaches the speed of light. Hence the circuit is capable of providing high velocity telephone channels with their well-recognized advantages. The fact that the velocity at high frequencies is substantially constant minimizes the correction required to bring the delay distortion within the limits required for a high quality television band.

Shielding and Crosstalk

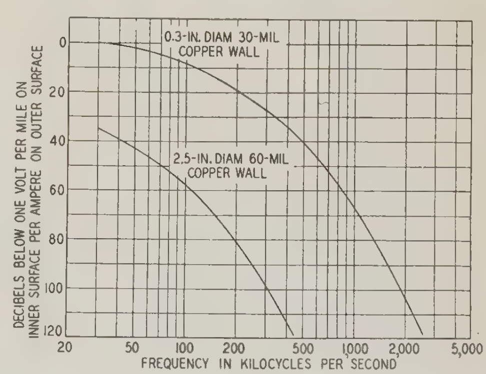
The shielding effect of the outer conductor of a coaxial circuit is illustrated in Fig. 9, where the transfer impedance between the outer and inner surfaces of the outer conductor is plotted as a function of frequency. There will be observed the sharp decrease in inductive susceptibility as the frequency rises. On this account, the crosstalk between adjacent coaxial circuits falls off very rapidly with increasing frequency. The trend is, therefore, markedly different from that for ordinary nonshielded circuits which rely upon balance to limit the inductive coupling. As a practical matter, less shielding is ordinarily required to avoid crosstalk than to avoid external interference.

With suitable design the shielding effect of the outer conductor renders the coaxial circuit substantially immune to external interference at frequencies above the lower end of the spectrum. Hence the signals transmitted over the circuit may be permitted to drop down to a level determined largely by the noise due to thermal agitation of electricity in the conductors and tube noise in the associated amplifiers. It appears uneconomical to make the outer conductor sufficiently thick to provide adequate shielding for the very low frequencies. Also it seems impractical to design the repeaters to transmit very low frequencies. Hence the best system design appears to be one in which the lowest 5 or 10 per cent of the frequency range is not used for signal transmission. The coaxial circuit is, however, well suited to the transmission of 60-cycle current for operating the repeaters, a matter which will be referred to later.

Broad-Band Amplifiers

In order to realize the full advantage of broad band transmission, the repeater for this type of system should be capable of amplifying the entire frequency band *en bloc*. Furthermore, it should be so stable and free from distortion that a large number of repeaters may be operated in tandem. Although high-gain radio frequency amplifiers are in every-day use, these are generally arranged to amplify at any one time only a relatively narrow band of frequencies, a variable tuning device being provided so that the amplification may be obtained at any point in a fairly wide frequency range. The high gain is usually obtained by presenting a high impedance to the input circuits of the various tubes through tuning the input and interstage coupling circuits to approximate anti-resonance.

Fig. 9. Shielding in a coaxial circuit



In amplifying a broad band of frequencies, it is difficult to maintain a very high impedance facing the grid circuits. The inherent capacitances between the tube elements and in the mounting result in a rather low impedance shunt which cannot be resonated over the desired frequency band. It is, therefore, necessary to use relatively low impedance

coupling circuits and to obtain as high gain as possible from the tubes themselves. The amount of gain which can be obtained without regeneration depends, of course, upon the type of tube, the number of amplification stages, the band width, and also upon the ratio of highest to lowest frequency transmitted.

Repeater Gain

The total net gain desired in a line amplifier is such as to raise the level of an incoming signal from its minimum permissible value, which is limited by interference, up to the maximum value which the amplifier can handle.

As pointed out above, the noise in a well shielded system is that due to resistance noise in the line conductors and tube noise in the amplifiers. In some of the repeaters which have been built, the amplifier noise has been kept down to about 2 db above resistance noise, corresponding to about 7×10^{-17} watt per voice channel. In a long line with many repeaters the noise voltages add at random, or in other words, the noise powers add directly. Assuming, for example, a line with 200 repeaters, the noise power at the far end would be 200 times that for a single repeater section. In general, the line and amplifier noise will not be objectionable in a long telephone channel if the speech sideband level at any amplifier input is not permitted to drop more than about 55 db below the level of the voice frequency band at the transmitting toll switchboard.

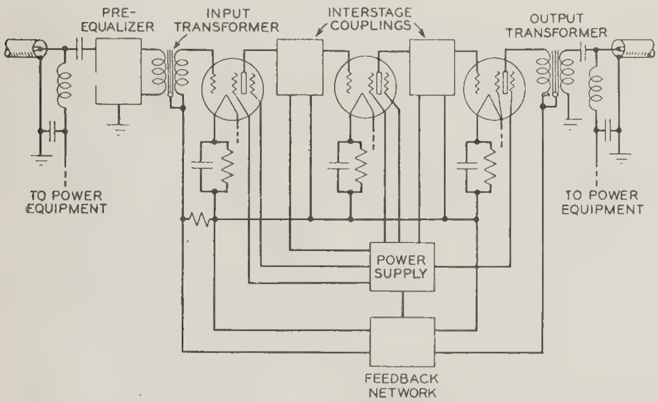


Fig. 10. Circuit of 1,000-kc 3-stage feedback repeater

The determination of the volume which a tube can handle in transmitting a wide band of frequencies involves a knowledge of the distribution in time and frequency of the signaling energy and of the requirements as to distortion of the various components of the signal. The distribution of the energy in telephone signals has been the subject of much study. This distribution is known to vary over very wide limits, depending upon the voice of the talker and many other factors. It is, therefore, obvious that the problem of summing up the energy of some hundreds of simultaneous telephone conversations is a difficult one. Enough work has been done, however, to indicate fairly well what the result of such addition will be.

Fig. 11. Gain of 1,000-kc repeater

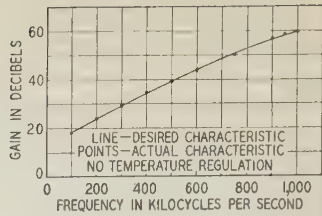
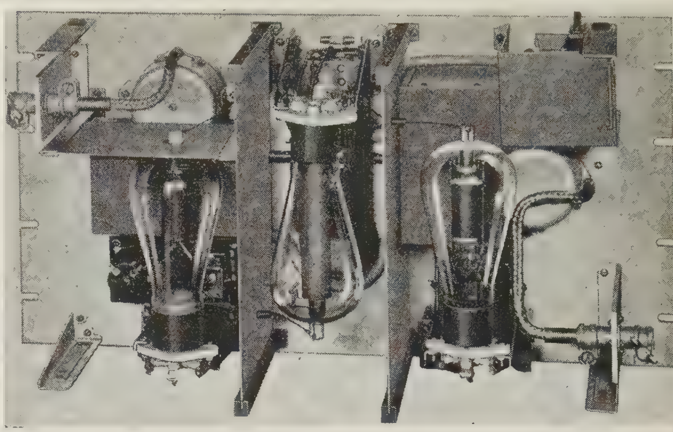


Fig. 12 (below). Photograph of 1,000-kc repeater



As to distortion in telephone transmission, the most serious problem has been to limit the intermodulation between various signals which are transmitted simultaneously through the repeater and appear as noise in the telephone channel. The requirement for such noise is similar to that for line and tube noise, and similarly it will add up in successive repeater sections for a long line. With present types of tubes operating with a moderate plate potential, the modulation requirement can be met only at relatively low output levels. To improve this situation and also to obtain advantages in amplifier stability, the reversed feedback principle employed for cable carrier amplifiers, as described in a paper by H. S. Black,[14] has been extended to higher frequency ranges. It has been found that amplifiers of this type having 30-db feedback reduce the distortion to such an extent that each amplifier of a long system carrying several hundred telephone channels will handle satisfactorily a channel output signal level about 5 db above that at the input of the toll line.

The maximum gain which can be used in the repeater, therefore, is, in the illustrative case given above of a long system carrying several hundred telephone channels, the difference between the minimum and maximum levels of 55 db below and 5 db above the point of reference, respectively, or a total gain of 60 db. (With a 0.3-in. coaxial line of the type shown in Fig. 2, this corresponds to a repeater spacing of about 10 miles.) If a repeater is to have 60-db net gain and at the same time about 30-db feedback, it is obvious that the total forward gain through the amplifying stages must be about 90 db. The circuit of an experimental amplifier meeting the gain requirements for a frequency band from 50 to 1,000 kc is shown schematically in Fig. 10.

Gain-Frequency Characteristic

As pointed out above, the line attenuation is not uniform with frequency. For a repeater section which has a loss of, say, 60 db at 1,000 kc, the loss at 50 kc would be only about 15 db. Such a sloping characteristic can be taken care of either by designing the repeater to have an equivalent slope in its gain-frequency characteristic or by designing it for constant gain and supplementing it with an equalizer which gives the desired over-all characteristic. Both methods have been tried out, as well as intermediate ones. In Fig. 11 is illustrated such a sloping characteristic obtained by adjusting the coupling impedances in a 3-tube repeater, designed in this case for 60-db gain at 1,000 kc. The accompanying photograph, Fig. 12, gives an idea of the apparatus required in such a repeater, apart from the power supply equipment.

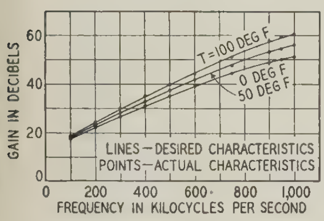


Fig. 13. Temperature regulation—line and repeater characteristics

Regulation for Temperature Changes

It is necessary that the repeater provide compensation for variations in the line attenuation due to changes of temperature. In the case of aerial construction such variations might amount to as much as 8 per cent in a day or 16 per cent in a year. If the line is underground the annual variation is only about $^1/_3$ of the above value and the changes occur much more slowly. On a transcontinental line the annual variation might total about 1,500 db. Inasmuch as it is desirable to hold the transmission on a long circuit constant within about ± 2 db, it is obvious that the regulation problem is an important one.

In a single repeater section of aerial line the variation might amount to ± 2.5 db per day or ± 5 db per year. Such variations, if allowed to accumulate over several repeater sections, will drop the signal down into the noise or raise it so as to overload the tubes. It is, therefore, advisable to provide some regulation at every repeater in an aerial line so as to maintain the transmission levels at approximately their correct position. For underground installations the regulating mechanism may be omitted on 2 out of every 3 repeaters.

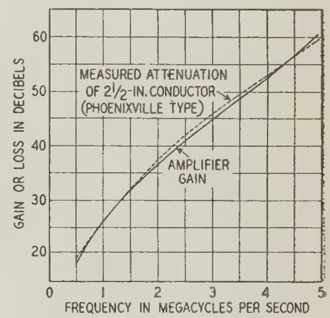
In choosing a type of regulator system the necessity for avoiding cumulative errors in the large number of repeater sections has been borne in mind. In view of the wide band available, a pilot channel regulator system was naturally suggested. Such a scheme employing 2 pilot frequencies has been used experimentally to adjust the gain characteristic in such a way as to maintain the desired levels throughout the band. The accuracy with which this has been accomplished for a single repeater section is illustrated in Fig. 13. Over the entire band of frequencies and the extreme ranges in temperature which may be encountered, the desired regulation is obtained within a few tenths of a decibel.

Repeater Operation, Power Supply, Housing, Etc.

In view of the large number of repeaters required in a broad-band transmission system it is essential that the repeater stations be simple and involve a minimum of maintenance. With the repeater design as described it is expected that most of the repeaters may be operated on an unattended basis, requiring maintenance visits at infrequent intervals.

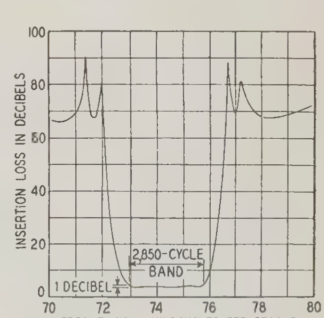
An important factor in this connecton is the possibility of supplying current to unattended repeaters over the transmission line itself. The coaxial line is well adapted to transmit 60-cycle current to repeaters without extreme losses and without hazard. The repeaters with regulating arrangements as built experimentally for a 1,000-kc system are designed to use 60-cycle current, which in this case appears to have the usual advantages over d-c supply. One repeater requires a supply of about 150 watts. The number of repeaters which can be supplied with current transmitted over the line from any one point depends upon the voltage limitation which may be imposed on the circuit from considerations of safety.

Fig. 14. Frequency characteristic of coaxial line and 5,000-kc repeater



For a repeater of the type described with current supplied over the line, only a very modest housing arrangement will be required. For the great majority of stations, it appears possible to accommodate the repeaters in weather-proof containers mounted on poles, in small huts, or in manholes.

Fig. 15. Frequency characteristic of quartz crystal channel band filter



Most of what has been said above applies particularly to repeaters transmitting frequencies up to about 1,000 kc. However, study has been given also to repeaters, both of the feedback and the nonfeedback types, for transmitting higher frequencies. Experimental repeaters covering the range from 500 to 5,000 kc have been built and tested. These were capable of handling simultaneously the full complement of over 1,000 channels which such a broad band will permit. The frequency characteristic of one of these repeaters, and the measured attenuation of a section of line of the type tested at Phoenixville, are shown in Fig. 14.

Terminal Arrangements

In order to utilize a broad band effectively for telephone purposes, the speech channels must be placed as close together in frequency as practicable. The factors which limit this spacing are: (1) The width of speech band to be transmitted; and (2), the sharpness of available selecting networks.

As to the width of speech band, the present requirement for commercial telephone circuits is an effective transmission band width of at least 2,500 cycles, extending from 250 to 2,750 cycles. It has been found that a band of this width or more may be obtained with channels spaced at 4,000-cycle intervals. Band filters using ordinary electrical elements are available,[3] for selecting such channels in the range from zero to about 50 kc. Channel selecting filters using quartz crystal elements[15,16] have been developed in the range from about 30 to 500 kc. The selectivity of a typical filter employing quartz crystal elements is shown on Fig. 15.

Initial Step of Modulation

The initial modulation (from the voice range) may be carried out in an ordinary vacuum tube modulator or one of a number of other nonlinear devices. The method chosen for the present experimental work employs a single sideband with suppressed carrier, using a copper oxide modulator associated with a quartz crystal channel filter. The terminal apparatus required for 2-way transmission over a 2-path circuit is shown diagrammatically on the left-hand side of Fig. 16.

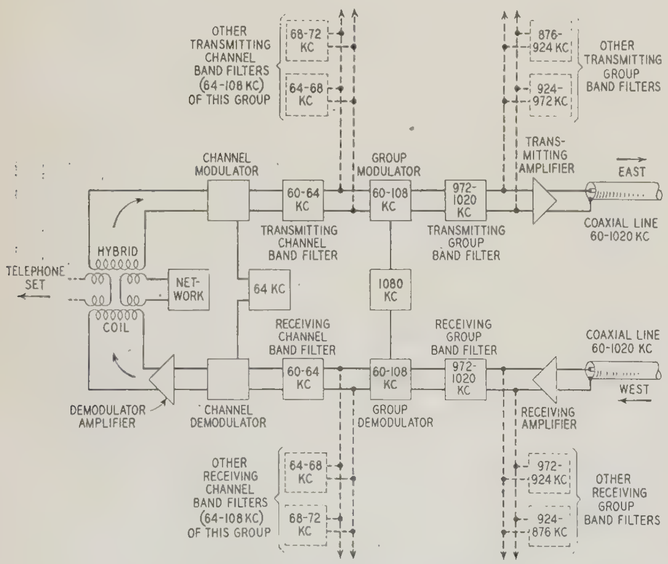


Fig. 16. Schematic diagram of 4-wire circuit employing 2 steps of modulation

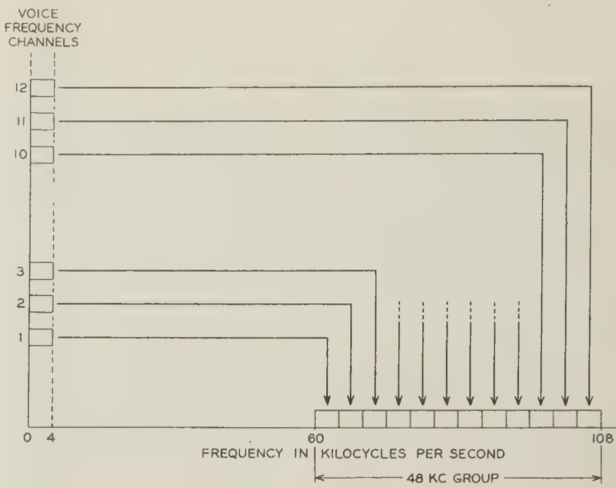


Fig. 17. Diagram illustrating frequency allocation for first step of modulation

A frequency allocation which has been used for experimental purposes employs carriers from 64 to 108 kc for the initial step of modulation. The lower sidebands are selected and placed side by side in the range from 60 to 108 kc, as illustrated in Fig. 17, forming a group of 12 channels.

Double Modulation

In order to extend the frequency range of a system to accommodate a very large number of channels, it appears to be more economical to add a second step of modulation rather than carry the individual channel modulation up to higher frequencies. Such a second step of modulation has been used experimentally to translate the initial group of 12 channels *en bloc* from the range 60 to 108 kc up to higher frequencies. It is possible to place such groups of channels one above another as illustrated in the upper part of the diagram of Fig. 18, up to about 1,000 kc, wasting no frequency space between groups and thus keeping the channels spaced at intervals of 4 kc throughout the entire range.

The apparatus required for this purpose is shown schematically in Fig. 16, which illustrates the complete terminal arrangements for a single channel employing double modulation. The figure indicates by dotted lines where the other channels and groups of channels are connected to the system.

A modulator for shifting the frequency position of a group of channels inherently yields many different modulation products as a result of the intermodulation of the signal frequencies with the carrier frequency and with one another. Out of these products

only the "group sideband" is desired. The number of the modulation products resulting merely from the lower ordered terms of the modulator response characteristic is extremely large. All such products must be considered from the standpoint of interference either with the group which is wanted in the output or with other groups to be transmitted over the system. Various expedients may be used to avoid interference as follows: (1) A proper choice of frequency allocation will place the undesired modulation products in the least objectionable location with respect to the wanted signal bands; (2) a high ratio of carrier to signal will minimize all products involving only the signal frequencies; (3) the use of a balanced modulator will materially reduce all products involving the second order of the signal; and (4) selectivity in the group filters will tend to eliminate all products removed some distance from the wanted signal group. Giving due regard to these

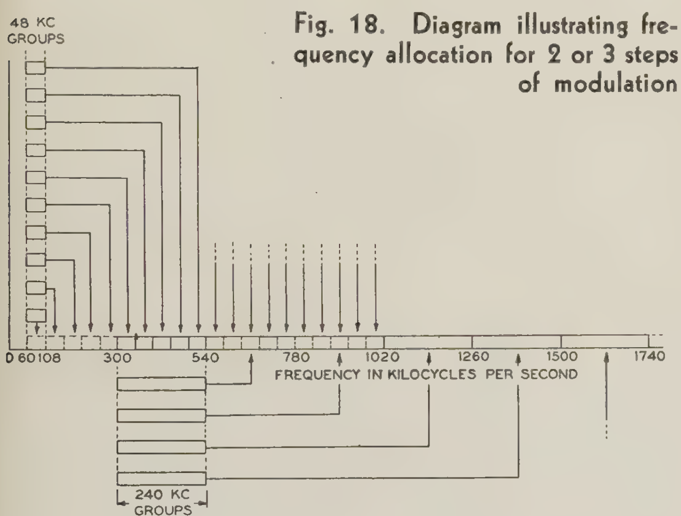


Fig. 18. Diagram illustrating frequency allocation for 2 or 3 steps of modulation

factors, balanced vacuum tube group modulators have been developed which are satisfactory for the frequency allocations employed.

Triple Modulation

For systems involving frequencies higher than about 1,000 kc it may be desirable to introduce a third step of modulation. In some experiments along this line a "super-group" of 60 channels, or 5 12-channel groups, has been chosen. The lower part of Fig. 18 illustrates, for a triple modulation system, the shifting of super-groups of 60 channels each to the line frequency position. This method has been employed experimentally up to about 5,000 kc. It is of interest to note that even in extending these systems to such high frequencies, channels are placed side by side at intervals of 4,000 cycles to form a practically continuous useful band for transmission over the line.

Demodulation

On the receiving side the modulation process is reversed. The apparatus units are similar to those used on the transmitting side, and are similarly arranged. This is illustrated in Fig. 16 for the case of double modulation.

Carrier Frequency Supply

In systems operating at higher frequencies it is necessary that the carrier frequencies be maintained within a few cycles of their theoretical position in order to avoid beat tones or distortion of the speech band. Separate oscillators of high stability could, of course, be used for the carrier supply but it appears more economical to provide carriers by means of harmonic generation from a fundamental basic frequency. Such a base frequency may be transmitted from one end of the circuit to the other, or may be supplied separately at each end.

Television

The broad band made available by the line and repeaters may be used for the transmission of signals for high quality television. Such signals may contain frequency components extending over the entire range from zero or a very low frequency up to 1,000,000 or more cycles.[4] The amplifying and transmitting of these frequencies, particularly the lower ones, presents a serious problem. The difficulty can be overcome by translating the entire band upward in frequency to a range which can be satisfactorily transmitted. To effect such a shift, the television band may first be modulated up to a position considerably higher than its highest frequency and then

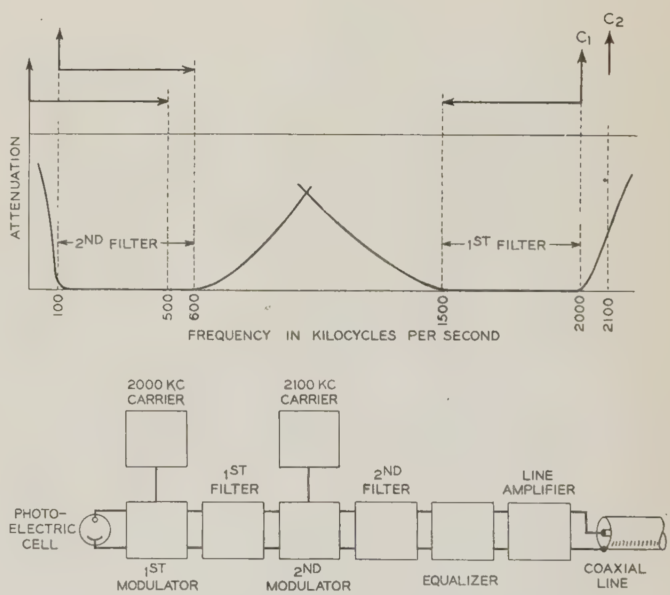


Fig. 19. Double modulation method of translating television signals for wire line transmission

with a second step of modulation be stepped down to the position desired for line transmission.

This method is illustrated in Fig. 19 for a 500-kc television signal band. The original television signal is first modulated with a relatively high frequency,

2,000 kc in this case (C_1). The lower sideband, extending to 1,500 kc, is selected and is modulated again with a frequency of 2,100 kc (C_2). The lower sideband of 100 to 600 kc is selected with a special filter so designed that the low frequency end is accurately reproduced. The television signal then occupies the frequency range of 100 to 600 kc as shown on the diagram and may be transmitted over a coaxial or other high frequency line. At the receiving end a reverse process is employed. The same method using correspondingly higher frequencies may be used for wider bands of television signals.

Other Communication Facilities

The telephone channels provided by the system may be used for other types of communication services, such as multi-channel telegraph, teletype, picture transmission, etc. For the transmission of a high quality musical program, which requires a wider band than does commercial telephony, 2 or more adjacent telephone channels may be merged. The adaptability of the broad-band system to different types of transmission thus will be evident.

As already noted, the commercial application of these systems for wide-band transmission over coaxial lines must await a demand for large groups of communication facilities or for television. The results which have been outlined are based upon development work in the laboratory and the field, and it is probable that the systems when used commercially will differ considerably from the arrangements described.

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A High Power Welding Rectifier

A welding rectifier embodying the "ignitron" principle, a recent development in a program of research on mercury arc rectifiers, provides predetermined welding currents for periods of time variable in steps of 1/120 sec, or less if desired. This paper describes the design and operation of the "ignitron" and illustrates its applicability to the problems involved in line welding processes.

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In SHEET METAL fabrication it is frequently desirable to fasten parts together by localized welds obtained by a combination of heat and pressure at a spot. Such welds are made electrically; the pressure is applied through the electrodes, and resistive heating is produced by the current at the contact surface between the 2 sheets and in the material itself. This process requires momentary currents, sometimes of very large magnitude. The short time is necessary to prevent the spread of the heat to adjacent portions of the material, particularly when working with heat treated metals. Exact control of time and current permits a weld as strong as possible without burning the material.

Contactors are used for spot welding, but their limitations as to speed of operation and the lack of accurate control of time of closure, particularly for the larger sizes, have limited their applicability to seam welding work. Consequently the most satisfactory means of controlling large welding currents utilize gaseous conduction devices.

In the field of low power apparatus there has been used effectively and variously a small grid-controlled arc-discharge device known as the "grid-glow" tube, or by any of several other names. Now, the "ignitron" in this form brings to the field of large power apparatus a similar tool—a positively

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 15, 1934; released for publication Aug. 18, 1934. *Not published in pamphlet form.*

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controlled low-loss arc-discharge device capable of carrying large currents and handling extreme overloads. Just as the smaller tube has enjoyed widespread application in the recent past, so the "ignitron" may be expected to lend itself successfully to a wide variety of problems.

The "Ignitron"

The "ignitron" has been described in previous publications (Slepian and Ludwig, A.I.E.E. Trans., v. 52, 1933, p. 693; Ludwig, Maxfield, and Toepfer, Elec. Engg., v. 53, Jan. 1934, p. 75–8; Knowles and Bangratz, *Elec. Jl.*, Dec. 1933; Knowles, *electronics*, June 1933). The principle of operation might be illustrated as follows: If a material of a certain order of resistivity, such as a crystal of carborundum, is immersed in a pool of mercury in a vacuum and a voltage is applied to the crystal (positive with respect to the mercury), a cathode spot will form on the mercury and an arc will start. In Fig. 1, A is an evacuated glass vessel holding a pool of mercury, C, electrically connected to lead, B. Immersed in the mercury is one end of a crystal of carborundum, D, supported from block E through seal F. Another electrode, G, is brought in from the side, and maintained at a positive potential with respect to B by the battery, H. If the switch, S, is closed, impressing battery potential on E, an arc will start at K, the junction of crystal and mercury. Current will flow first from E to C, then between the anode, G, and C, the current being limited mainly by circuit impedance.

Developed to its present state, the ignitron combines the properties desirable in a rectifier with many features heretofore unavailable in most arc discharge devices. With the mercury pool type of cathode, unlimited peak currents are possible without destructive effects, permitting extreme momentary overloads. The igniter gives positive control of the starting of the arc; there is no holding arc; and after the zero of current the arc space quickly deionizes and remains so until time for the next cycle of current when the arc again is started. Because of this lack of ionization during the time the anode bears negative voltage, the anode need not be protected by shields and grids. With the resulting short unrestricted arc, the arc potential drop is low and the losses small. Arc-back occurs very infrequently in the ignitron because it is only during a few microseconds after current zero that an arc-back danger exists.

Novel properties of the ignitron are: (1) its positive and inherent control, (2) low loss at all loads coupled with low frequency of arc-back, and (3) its overload capability. This combination is found in no other equipment, and is sufficient to recommend the ignitron for many interesting applications, particularly those making use of its control features. It is suitable for any application demanding positive control of large currents, where intermittent operation at rather high frequency is necessary. One such application is its use as a controlling switch in spot or seam welding. Because of its high current capacity and low arc drop, the ignitron can be used directly in a low voltage circuit and so obviates the necessity of transforming apparatus to connect it into the welding circuit. The welding current passes directly through the ignitron and is maintained at zero value as long as the igniter is blocked. The use of the mercury pool cathode provides an inherent overload capacity and long life.

Ignitrons in small sizes, constructed of glass, have been used extensively for spot welding. While the peak current may be very high in such applications, the frequency of the spots (or the duty cycle) is so low that the average current is low and the physical size can be small. This paper deals only with the large-power steel-tank welding ignitron.

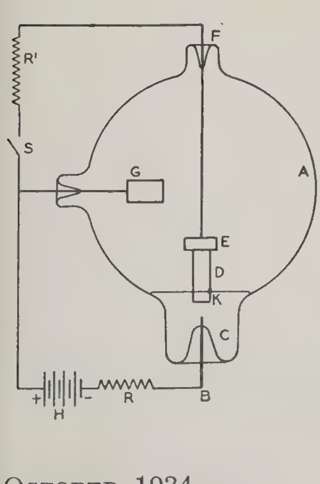

Fig. 1 (left). Diagram illustrating the "ignitron" principle

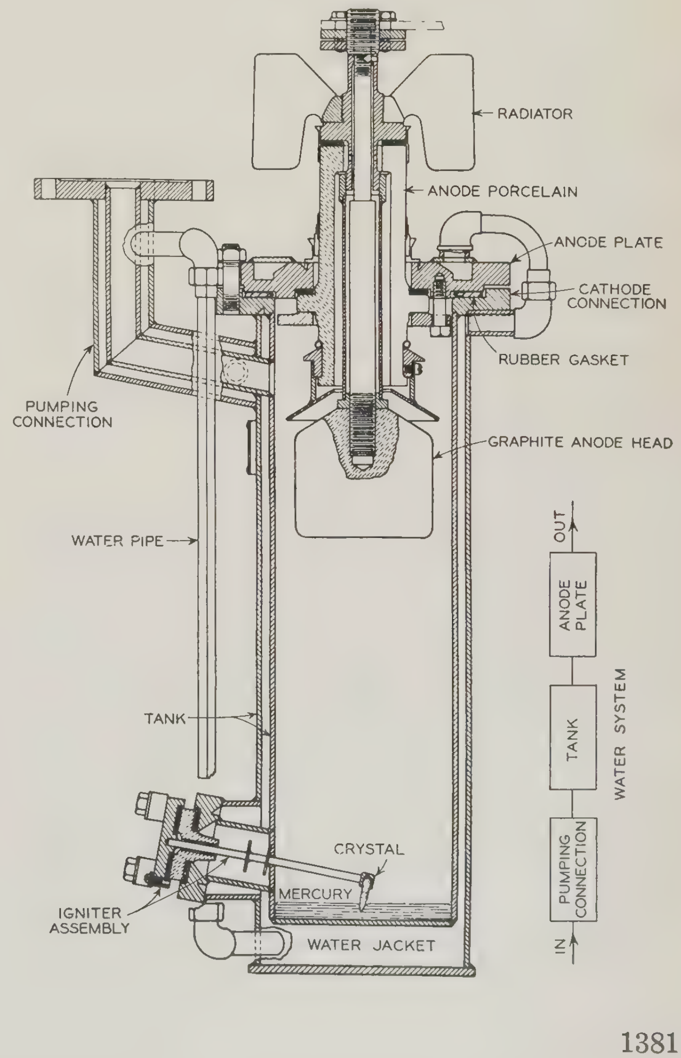

Fig. 2 (right). Cross-sectional view of the "ignitron" welding rectifier

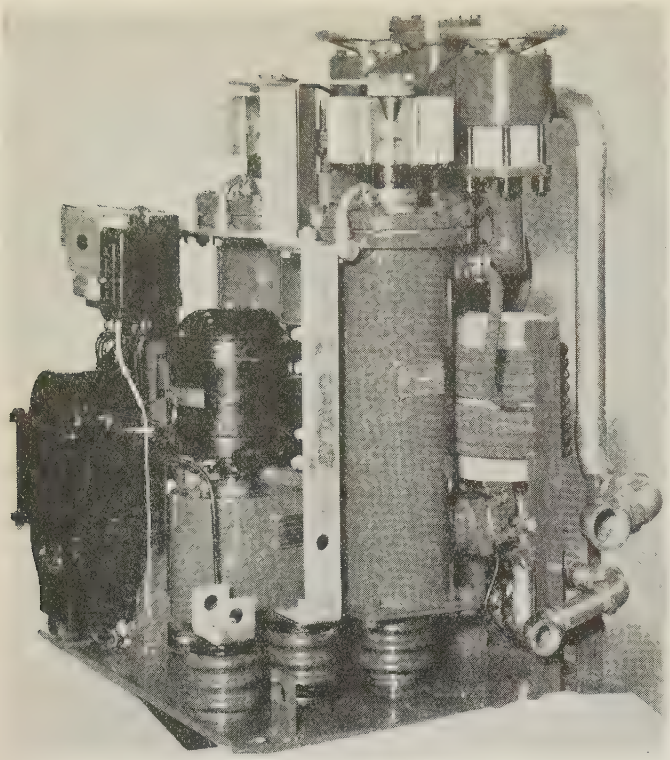

Fig. 3. Complete rectifier assembled

CONSTRUCTION OF THE RECTIFIER

As shown in Fig. 2, the present design of welding ignitron comprises a water cooled tank about 5 in. in diameter and 17 in. long with a graphite anode 4 in. in diameter supported from a porcelain insulator. The igniter is supported by a steel rod brought in from the side on a rubber sealed porcelain insulator. The anode assembly is practically the standard unit as used for several years in the 500-kw 600-volt conventional steel-tank rectifier.

Inasmuch as the arc in the ignitron goes out at the end of the period of conduction and must start again each cycle at the igniter, which is approximately in the center of the tube, the greatest radial distance that the spot can travel in the time of one cycle is limited by the time of conduction and the speed of motion of the spot. If this distance is less than the radius of the pool, there is no danger of the cathode spot reaching the tank wall. It is possible, therefore, to discard the conventional quartz guard ring and porcelain insulator and to connect the cathode and tank electrically.

The igniter is a small crystal of carborundum, cast in nickel in a steel hub. The latter is threaded on an insulated steel rod brought in from the side and fastened to the tank wall with insulated bolts.

The entire construction is according to standard practice in steel tank rectifier design, employing solder-to-porcelain and rubber seals. Pumping is provided through a water cooled arm entering near the top of the tank. Insulating sections are provided between the ignitrons and a small manifold which connects directly to the mercury pump. The use of rubber seals and bolted flanges makes it extremely convenient to open, inspect, and repair these rectifiers. The igniter may be removed and replaced through the side opening without disturbing the anode plate.

Figure 3 shows the complete assembly of ignitron, pumps, and cooling and protective equipment. This is a self-contained unit including all auxiliary, electrical, and water connections ready to be connected to the controller, power, and water circuits. The vacuum pumping equipment includes a mercury vapor pump and a rotary oil sealed backing pump, and is arranged for automatic intermittent operation of the rotary pump as needed to maintain a satisfactory vacuum.

A typical diagram of connections when used as a line welder is shown in Fig. 4. The 2 ignitrons are directed oppositely and in parallel; together they act as a switch in the circuit between the power transformer and the step-down transformer at the welding machine. Each igniter is connected to its own anode through a small grid-controlled rectifier, through which the starting energy passes. The control circuits end at the grids of these auxiliary rectifier tubes. The control circuit shown in Fig. 4 indicates a mechanical contactor as used in the early tests. A more flexible and positive controller, using a synchronously driven disk with a photo-electric pick up, is described in a paper, "A New Timer for Resistance Welding" by R. N. Stoddard (see p. 1366–70 of this issue). These controllers operate to impress a bias on the grid at the desired moment, the time when conduction starts depending upon when this bias becomes positive. The grids of the second set of auxiliary rectifier tubes are available for further control of the welding current within the period of conduction set by the master controller.

OPERATION AND LIMITATIONS

The ignitron requires a certain minimum voltage on the igniter before the arc can start. If this starting voltage comes from the anode, as it usually does, (Fig. 4) rather than from a separate excitation circuit, no arc can start until the anode potential reaches this minimum value. For voltages much greater than this minimum striking voltage the starting action is exceedingly rapid, a cathode spot forming in 1 or 2 μsec. From this point of view the welding circuit, which is of rather low power factor, is advantageous in that the anode voltage rises, after current zero in the other ignitron, to almost peak line voltage and so provides a considerable overvoltage for rapid igniter action.

Low power factor conditions in general increase the difficulty of circuit interruption, because the rapid rate of rise of back voltage after current zero makes it difficult to prevent restriking of the arc. In a rectifier such a restriking is called an arc-back. However, in the welding circuit, the back voltage on one ignitron is limited to striking voltage or arc drop in the other except at the end of the last half cycle of the current group when the current is interrupted. Thus, notwithstanding the low power factor circuit, the tendency to arc back is much less than for the same ignitrons in 6-phase rectifier operation; practically, it is less in the ratio of the num-

ber of duty cycles per second to 360, which may be as small as a few per cent. Furthermore, the welding ignitrons are in operation only while work is actually between the rolls of the welder. This must be considered in interpreting the test results to follow.

Probability of arc-back seems to be highest in the short period after current zero while the anode bears negative voltage and an ionized gas exists between the 2 electrodes. The higher the vapor pressure the longer the time required for the density of ionization to be reduced to a value sufficiently low to withstand negative anode voltage safely. The lower the temperature of existing mercury surfaces the lower the vapor pressure and the lower the arc-back rate. It has been observed both in the laboratory and in service that the arc-back tendency is satisfactorily low at water temperatures as high as 45 deg C (104 deg F).

Seam welding service is not particularly exacting as regards arc-back. Service is not interrupted, and the only result is the possibility of one extra half cycle of current. The probability of arc-backs on successive half cycles is practically zero. It has been observed that many other variables are involved in the welding process, such as particles of dirt under the rolls, small roughnesses on the work, or variability in the surface oxide; these variables are much more frequent in occurrence and have a much greater effect on the character of the weld than an extra half cycle of current or an arc-back in the ignitrons.

Individual igniters may be expected to vary slightly in characteristics, one from the other, and variations in starting action from cycle to cycle for a given igniter may be as great as differences between 2 igniters. The effect of these variations tends to become smaller the higher the circuit voltage. However, the control circuit makes it possible to correct for any dissimilarity in average starter characteristics or in arc drop in the 2 ignitrons. The starting can be controlled so that the d-c component of current in the line is a fraction of one per cent of the current through each ignitron.

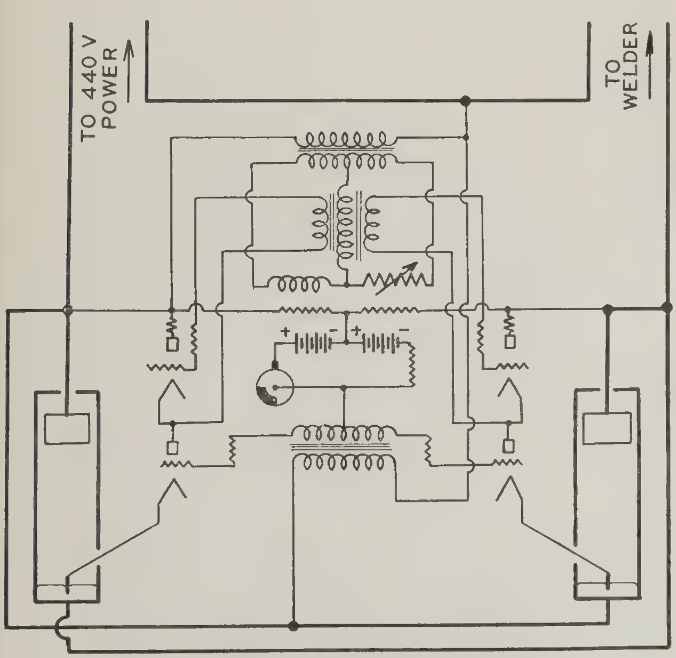

Fig. 4. Wiring circuit for seam welding

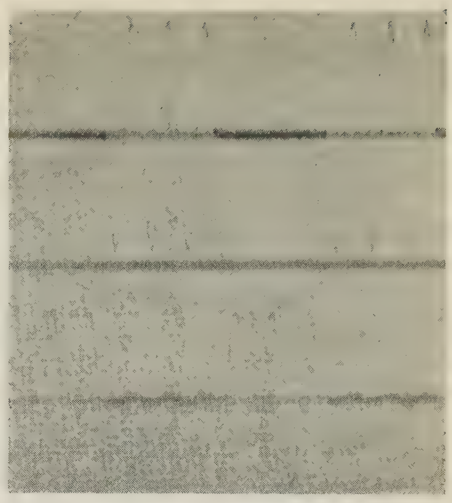

Fig. 5. Oscillogram of rectifier output while operating at full load

Top trace, line current (peak, 2,100 amp); middle trace, igniter current in one "ignitron"; lower trace, voltage between anode and cathode (peak, 575 volts)

Service Record

Since the first welding units were built and tested considerable operating data have been accumulated, both in the laboratory and in the field. At present, 5 units are in commercial operation: 1 welding stainless steel beer barrels, 1 aluminum beer barrels, and 3 bronze refrigerator evaporators. One of these uses a 50-per cent duty cycle with a peak current of 500 amp. Another uses a 23-per cent duty cycle with 1600 amp peak and 120 amp average per tube. All have given several months of satisfactory service. In the laboratory, extensive tests have been made under various conditions of temperature, load, and duty cycle. Even under severe conditions of all 3 variables the operation was extremely gratifying.

An oscillogram of the operation of ignitrons in welding service is shown in Fig. 5. The ignitrons were operating on a 50-per cent duty cycle (3 cycles on and 3 off) with current limited by the circuit constants. In other words, no artificial delay was introduced other than that necessary to strike the arc with the igniter. As closely as can be judged by eye, there is coincidence between the dropping to zero of current in one ignitron and the building up of current in the other. The delay introduced by the igniter is not sufficient to cause any appreciable variation from a sine wave of current through the welding transformer. This oscillogram was taken with approximately 800 amp (rms) in the line and 240 amp (avg) in each ignitron.

With loads up to 100 amp (avg) per ignitron with outlet water 60 deg C (140 deg F) no arc-backs were observed in 4 hours' running. At 160 amp with 60-deg water an arc-back rate of about 1 per hour was observed. At the same temperature and 240 amp, the rate was about 10 per hour. However, with this latter load and 40 deg C (104 deg F) water temperature the arc-back rate was less than $^1/_3$ per hour. This was for 50-per cent duty cycle and peak currents of about 2,000 amp. Peak currents as high as 2,500 amp were carried with an arc drop of about 16 volts.

The "Ignitron" Type of Inverter

The operation of inverters for obtaining alternating current from direct current is first considered in this paper, both the grid controlled rectifier and the "ignitron," a special type of mercury vapor tube, being analyzed. The duty on the inverter tube is next discussed, and special attention is then given to the "ignitron" inverter. Experimental results obtained with this latter type of inverter are given.

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THE ability of the grid controlled rectifier to prevent current conduction until some predetermined point during the cycle has led to its suggestion for application to a large number of different uses among which may be mentioned voltage control of rectifiers, conversion from direct current to alternating current, commonly called inversion, and also frequency conversion. A new form of rectifier known as the "ignitron" provides another and in some respects better device for these same applications. Briefly, the ignitron consists of a mercury pool cathode and a closely spaced anode. A small current passing through a silicon carbide crystal dipping into the mercury is used to initiate the main arc between the anode and cathode. It is the province of this paper to discuss the characteristics of ignitrons in relation to the special problems arising in inverting d-c energy to a-c energy.

Operation of Inverters

Both the grid controlled rectifier and the ignitron control the instant at which conduction takes place but thereafter lose control completely. Current in individual tubes must be interrupted or commutated through the medium of the external circuit which causes the current in the tube to decrease to zero. At the instant of current zero the insulating property of the tube is reëstablished and continues so until rendered conducting again by operation of the control features.

Inverters may be grouped into 2 general classes according to the means employed to effect this current zero, namely, inverters with static loads and inverters with loads having a rotational counter electromotive force. With static loads condensers in some form must be provided so that their charge or discharge will cause the current in the anode to be commutated to zero. For the second type, the phase position of the rotational electromotive forces may be so adjusted that when 2 or more tubes are made conducting simultaneously, the current in the first one to be made so conducting will decrease to zero. Examples of the former are polyphase lighting loads and single-phase neon sign lighting in d-c districts. Of the latter, examples are provided by induction and synchronous motors. In order to illustrate the requirements of these 2 general types the operation of a single-phase inverter with resistance load and also an a-c generator connected through an inverter circuit which corresponds to a d-c commutatorless motor will be discussed.

In Fig. 1 is shown a schematic diagram for a single-phase inverter with a resistance load. The constant potential E is applied from the d-c source and tubes A and B are alternately made conducting through the functioning of their control devices, the frequency of the a-c load being determined by the frequency of the control. Assume for the moment that tube A is conducting. Condenser C assumes a potential of approximately $2E$, the right-hand side being positive. Now if tube B is rendered conducting condenser C discharges through the 2 tubes causing the current in tube A to decrease to zero. Tube A thus becomes open-circuited. The anode-cathode potential is then equal to the potential across the condenser minus the arc drop in tube B. Since the left-hand side of the condenser is negative in potential relative to the right-hand side, the anode becomes negative relative to the cathode. With the new conduction paths, the condenser tends to charge in the opposite sense and as it becomes charged the anode-cathode potential increases from a negative value to a positive value as shown by the curve in Fig. 1*b*. The smaller the commutating condenser the more rapid will be the rise in anode-cathode potential. When tube A is made conducting the condenser discharges in the reverse sense extinguishing the arc in tube B. In this manner tubes A and B are alternately made to conduct current. Pulses of current are alternately made to pass through the 2 sides of the transformer which produce an alternating current in the secondary of the transformer and in the load resistance. Since the reactance of the transformer is low the current in the load resistance has the same wave shape as that of the voltage across the condenser. The requirements for the tube for this application are that it withstand a back voltage immediately after current zero of substantially twice the applied d-c voltage and a forward voltage which rises to approximately twice the d-c voltage after the elapse of a short time. Some control is possible over the rate of rise of the voltage but, in general, the shorter the time as dictated by the characteristics of

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the tube when positive potential is permitted, the smaller the condenser.

A counter electromotive force load as exemplified in the commutatorless d-c motor is shown schematically in Fig. 2. The machine consists of a conventional synchronous a-c generator or motor with damper windings. The particular connection shown is known as a 6-phase connection with delta secondary. The problem is to produce current pulses in the 6 phases. This requires that the current be built up and reduced again to zero. The counter or generated electromotive forces of the machine are e_1, e_2, e_3, and their negatives e_4, e_5, e_6. The instantaneous values of these voltages together with the applied d-c voltage are shown in Fig. 3. It will be assumed that the ballast inductance in the d-c side is so large as to justify the assumption of constant current in the d-c side. Suppose that tube 1 is carrying current and tube 2 is ignited. In order that i_1 decrease and i_2 increase it is necessary that the instantaneous value of e_1 exceed that of e_2. Thus, the ignition point for tube 2 must lead the instant when e_1 and e_2 are equal. Furthermore, commutation must be completed before e_1 becomes less than e_2. As the ignition point is advanced the duration of the commutating period decreases but the power factor becomes worse. The ideal condition is that i_1 reach zero just before e_1 and e_2 become equal.

The commutation process in reality constitutes a short circuit between terminals 1 and 2. After commutation is complete, i_1 has reduced to zero and i_2 has increased to the value i_1 had before commutation. The current in tube 2 remains at this constant value until tube 3 is made conducting. The process thus continues.

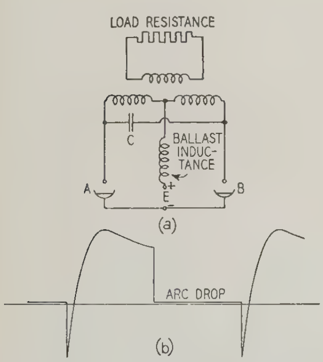


Fig. 1 (above). The static inverter, showing (a) schematic diagram, and (b) anode-cathode voltage

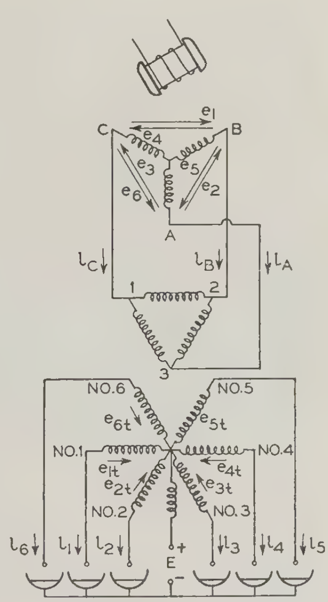
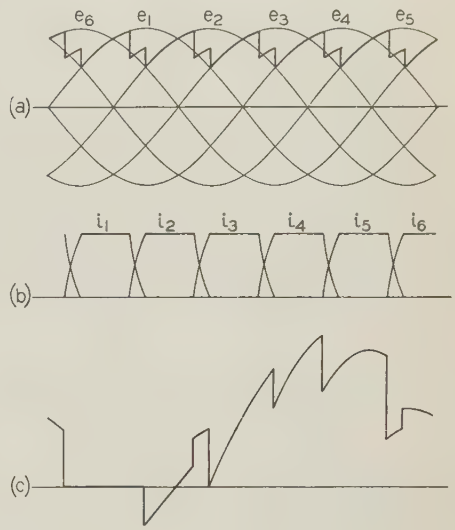


Fig. 2 (right). Schematic diagram of a commutatorless motor

During the intervals when only one tube is conducting, the voltages e_{1t}, e_{2t}, etc., in the transformers are equal to their corresponding generated electromotive forces because of the assumption of constant current in the d-c side. During the commutating periods, the transformer voltages of the 2 tubes being commutated are equal to the mean of the 2 corresponding generated voltages. The net voltage producing a back electromotive force to the applied voltage is that shown by the heavy line in Fig. 3. The average value of this line must equal the applied voltage. The instantaneous difference in voltage is absorbed by the ballast inductance.

Fig. 3. Operation of 6-phase inverter

a. Voltage between transformer neutral and cathodes of tubes
b. Anode currents
c. Anode-cathode voltage across tube 1



Immediately after the anode current in an individual tube passes to zero the anode-cathode voltage of that tube drops to a negative value. This is a necessary condition that follows from the commutation requirements. The shape of the anode-cathode voltage may be obtained from the transformer voltages e_{t1}, e_{t2}, etc. Consider that of tube 1. During its conducting period the voltage is, of course, the arc drop or if in this discussion the arc drop be neglected, it is equal to zero. To simplify the discussion still further, assume that the transformer impedances are zero. While one tube only is conducting, the anode-cathode voltage of tube 1, is equal to the transformer voltage of the tube minus e_{1t} or, to be specific, if tube 2 is conducting, the anode-cathode voltage of tube 1 is equal to $e_{21} - e_{1t} = e_2 - e_1$. While any 2 adjacent tubes are conducting, the transformer voltages of the phases not coupled with the phases involved are zero. Thus, suppose tubes 2 and 3 are conducting, $e_{2t} = e_{3t}$, which since the transformers have zero impedance, requires that the potential of points 1 and 2 above point 3 on the delta side of transformer be equal. Points 1 and 2 are then of the same potential and $e_{1t} = 0$. The anode-cathode potential of tube 1 while tubes 2 and 3 are conducting is equal to e_{2t} which is equal to $^1/_2(e_2 + e_3)$. Similar considerations apply when tubes 5 and 6 alone are conducting, the anode-cathode voltage of tube 1 being equal to $^1/_2(e_5 + e_6)$. Because of the coupling between phases, the anode-cathode voltage of tube 1 while tubes 3 and 4 alone are conducting is equal to $2e_{3t} = e_3 + e_4$. The anode-cathode voltage based upon the above assumption is shown in Fig. 3. In general the magnitude of the negative kick and the shape of the anode-voltage curve vary with the angle of ignition, the load, reactances of the ballast, trans-

formers and machine, characteristics of the machine, and the number of phases which are simultaneously conducting. The tubes must be able to operate without back-firing under the negative voltage imposed immediately after commutation and without forward-firing when the positive potential is applied.

For the particular inverter circuits discussed, early ignition requires that inverters operate at leading power factors. In general, the shorter the interval permissible between current zero and when positive potential may be applied, the better the power factor at which the inverter will operate. These inverters cannot supply lagging reactive volt-amperes. If the a-c load on the inverter requires lagging reactive volt-amperes provision must be made to supply it by some other device.

The Duty on the Inverter Tube

An inverter tube passes through 3 phases during one complete cycle of operation. The first of these phases may be termed the conducting period. As shown in the preceding section, the wave form of the current in the inverter tube is such that in a very short period of time the current must increase from zero to its maximum value. Thus the onset of conduction must be very rapid. Furthermore, this is a matter of more importance in inverter operation than in rectifier operation because successful commutation of the inverter depends upon accurate starting at fixed time intervals as well as a low arc drop within the tube from the instant when conduction is initiated. If these 2 conditions are not fulfilled, the time required for commutation is apt to overrun the allotted period with the result that the inverter fails. In the rectifier, an occasional commutating period of extra long duration, or the delayed starting of one tube, would pass unnoticed; but in certain kinds of inverter tubes, special means to insure a rapid onset of conduction must be resorted to.

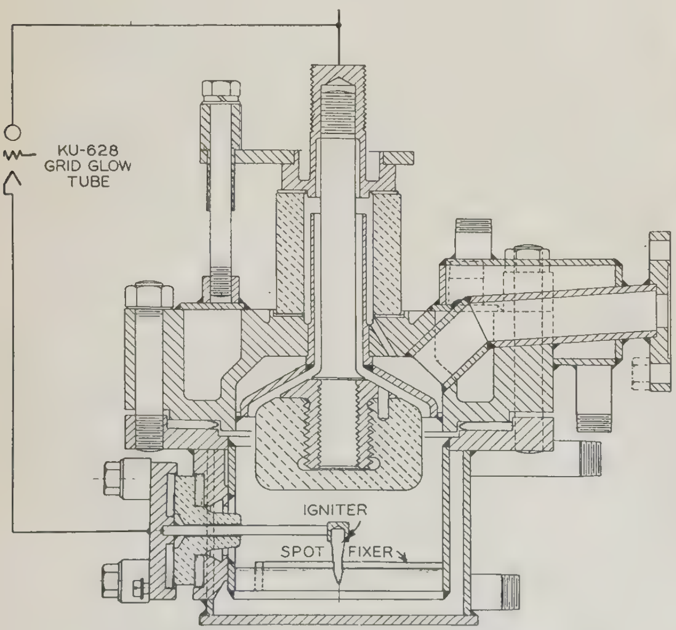


Fig. 4. Cross-sectional view of an ignitron. The over-all height of the tube shown is 10.5 in.

The second phase of inverter tube operation may be termed the rectification period. When the current in a given tube is reduced to zero by the commutating electromotive force, its rectifying property prevents the phenomenon which in rotating conversion machinery is known as over-commutation. This rectifying property is not possessed by brushes and commutators, and it is a considerable advantage of the tube type of equipment, because the commutating electromotive force in case tubes are used does not have to be made equal to a predetermined value, but it needs to be equal to or greater than this value. As in the case of the rectifier tube, the anode quickly becomes negative with respect to the cathode at the end of the conducting period. During the short interval of time throughout which the anode remains negative, there is a certain probability that the tube will back-fire. This phenomenon is of much less importance in the inverter than in the rectifier; however, a back-fire in an inverter does not short-circuit the d-c system, and in a fraction of a cycle the reverse current which flows in the event of a back-fire, will fall to zero. The back-fire is quite undesirable, however, because it may greatly increase the probability of a failure during the third phase of operation.

This third phase may be termed the positive control period. In a polyphase inverter it is the longest period of the cycle. The tube anode is positive with respect to the cathode throughout, but in spite of this the tube must be provided with means for pre-

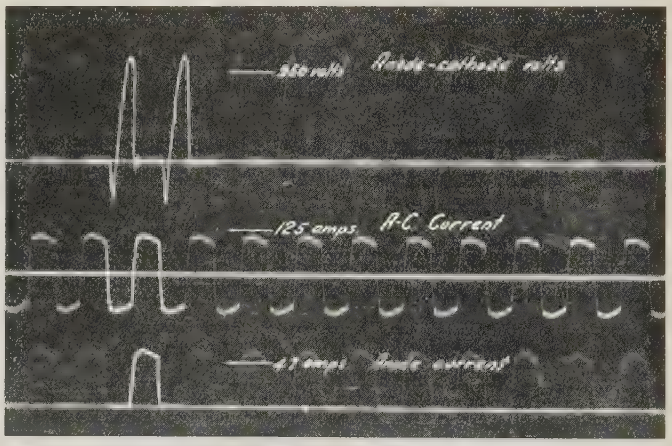


Fig. 5. Oscillogram of single-phase inverter operation with machine load. 159 cycles

venting the formation of an arc until the conduction period is reached. The accidental formation of an arc during the positive control period may be termed forward-fire. The probability of such a failure with any of the known inverter tubes depends upon the peak value of the current carried by the tube and also upon length of the rectification period, and if that period is short, also upon the manner in which positive voltage is applied to the anode. Practically, a long rectification period is not a satisfactory means for easing the duty on the inverter tube during the positive control period, because of the poor power

factor which would result. When an inverter supplies a load having a sinusoidal voltage wave form, positive voltage is applied to the inverter anode approximately sinusoidally, and this considerably simplifies the building of inversion equipment.

From this description of the duty on an inverter tube, it is evident that any of the known types of gaseous rectifiers could be used for inversion, provided they were equipped with some means for blocking conduction throughout the positive control period. The generally adopted means has been the introduction of an electrostatic control grid placed between the anode and the cathode. Such a grid has the property that if it is properly constructed and given a sufficient negative potential bias with respect to the cathode, a continuous positive ion space charge sheath will be formed around it which will prevent the formation of a current conducting arc. When conduction is desired, the grid is made positive.

Such grids have been applied to tubes of the single anode type which employ a thermionic cathode, and also to multi-anode tubes using a mercury pool cathode. The thermionic cathode inverter tube is well suited to those applications which only require small currents. In the larger sizes, the limitation of the cathode in current carrying capacity, the comparatively short life, and the limitations of the grid type of control have prevented any considerable application. The mercury pool cathode inverter has also been restricted by the limitations of the grid type of control. While it is free from the other disadvantages of the thermionic cathode type of tube, it suffers from a cumbersome and costly type of construction necessitated by the problem of restricting back-fire and forward-fire. This problem of forward-fire is a serious limitation to the satisfactory operation of inverters, and although tubes can be constructed which are sufficiently reliable, their cost and comparatively large losses have so far prevented any considerable application.

The "Ignitron" Inverter

The recent invention of a new method for initiating the cathode of an arc by Slepian and Ludwig (see "A New Method for Initiating the Cathode of an Arc," by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., 1933, v. 51, p. 693–8) has led to the development of a new type of tube called the "ignitron." In Fig. 4 is shown a cross-sectional view of an ignitron, which has been tested in an inverter circuit. The tube consists of a mercury pool cathode at the bottom of a small tank of very simple design, a graphite anode insulated from the tank, and an igniter electrode which is also insulated. No insulation of the cathode from the tank is required.

The anode is spaced close to the cathode, and no grids or shields intervene between the 2. Consequently, the arc drop during the conducting period is low, and at the onset of this period, the tube quickly becomes highly conducting without requiring any special system of excitation other than the igniter electrode. This electrode is of silicon carbide. Its lower end is immersed in the mercury and the upper end is welded into the holder. When current of a few amperes is caused to flow through the rod in the direction of holder to mercury, the cathode of an arc will be started on the mercury in a few millionths of a second. The action of the igniter has been completely described in the paper mentioned in the preceding paragraph. The required accuracy of control is an important feature found in the ignitron.

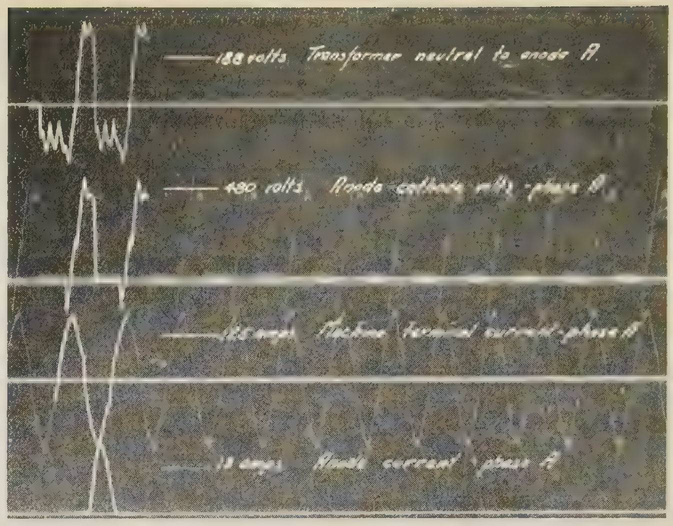


Fig. 6. Oscillogram of 6-phase inverter operation on 250-volt d-c circuit with synchronous machine load. 142 cycles

During the rectification period, the ignitron is able to withstand negative voltage without failure despite the proximity of anode and cathode, because of the absence of any source of ionization during this interval. It is only necessary to keep the density of the mercury vapor sufficiently low so that the residual ions from the conducting period will vanish quickly after the current becomes zero. The special means used for fixation of the cathode spot of the arc, shown in Fig. 4, are chiefly for this purpose. A complete description of the action within the ignitron during rectification has been presented by Ludwig, Maxfield and Toepfer ("An Experimental Ignitron Rectifier," Elec. Engg., v. 53, 1934, p. 75–8). Thus, it is evident that during the rectification period, the small size and high efficiency realized in the ignitron rectifier, are also present in the inverter.

During the positive control period, the ignitron functions in an essentially different way than the grid controlled tube. With grid control, the cathode is always in a live state of emission, and the grid has a preventive duty to perform. That is it must resist the formation of the plasma of an arc. In the ignitron, the cathode is normally in a nonemitting state, and the igniter has the duty of initiating conduction within the cathode region.

The first advantage of this type of control is the complete absence of the grid from the conducting path within the tube. The igniter electrode in no way hinders the conduction of the arc after it has formed, whereas the grid does do so, and adds about 2 volts to the arc drop. In addition, the control grid is often a source of trouble within the tube since conditions are difficult to avoid under which it will be burned by the arc.

The starting current is easily supplied to the igniter electrode at the proper time by the circuit shown in Fig. 4. A small thermionic cathode tube is connected between the anode of the ignitron and its starting electrode, and this tube may be grid controlled. It is quite small in size, because the average current of the igniter is only a fraction of an ampere. With this circuit, the effect has been to remove the grid from the main tube, and place it in an auxiliary tube where it in no way interferes with the conduction of the inverter current. The arrangement for operating the igniter is quite flexible, of course, and many other circuits are useful for special applications.

The second advantage of the igniter type of control is associated with the forward-firing probability. In the grid-controlled tube, the grid can only prevent conduction after a positive ion space charge sheath has formed about it. The thickness of this sheath depends upon the density of ionization. Since it is impractical because of too high an arc drop to use a grid with highly constricted passages, the density of ionization must be only a few per cent of that during the conducting period if the space charge sheath is to be sufficiently thick to make the grid effective. Thus, it is generally necessary to allow for a "deionization" time of a few hundred microseconds after current zero before considerable positive voltage is applied to the anode. Even after the grid has blocked the tube, there is no assurance that the accidental formation of a cathode spot upon the grid itself will not destroy the blocking action. Thus, either a failure of the grid to block initially, or a "back-fire" to the grid, will cause a forward-fire within the inverter tube.

In the ignitron, no space charge sheath needs to be formed about a grid, but at the cathode region itself. This sheath is of very small dimensions, however, and it can be shown that its formation, or "loss of a cathode spot" as the phenomenon has been termed, requires only a few microseconds instead of a few hundred. Afterward, there is, of course, no assurance that the accidental formation of a cathode spot on the cathode will not permit a forward-fire, and in this sense the ignitron will also have a "deionization" time. This deionization time is of a statistical nature, however, because of the random nature of the "back-fire" phenomenon (see "Backfires in Mercury Arc Rectifiers," by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., v. 51, 1932, p. 92–104). That the ignitron inverter can be made to run reliably, and still retain its inherent advantages of small size and low loss, will be shown by the experiments which will be described.

Experimental Results

In order to test their performance, 2 ignitrons were set up for a single-phase operation. The load consisted of a 100-kva 3-phase 180-cycle synchronous generator equipped with damper windings. Two terminals were connected to the 302-volt windings of 2 50 kva transformers, the 440–880-volt windings being connected through the ignitrons and ballast inductance to the 250-volt shop d-c circuit. A resistance of 0.25 ohm was also placed in series in the d-c supply to limit short-circuit currents. Control of the ignitrons was provided through the medium of a phase shifter connected to the 3 machine terminals, the secondary of the phase shifter supplying by means of a peaking transformer, voltage impulses to the grid glow tubes in the starter circuits. The oscillogram reproduced in Fig. 5 is a typical record of the results obtained. The anode-cathode voltage shows the negative kick as the current goes to zero and also the subsequent rise to a positive value. At 250 volts direct current, 140 amps, or 35 kw, were inverted by 2 tubes of the kind shown in Fig. 4 from direct current to 180 cycles alternating current, and during a 100 hr test there were no failures. The temperature of the cooling water in the tubes was from 35 deg C to 40 deg C throughout the test. The arc drop in the tubes was very substantially less than that of the conventional rectifier. At 500 volts direct current, 100 amps or 50 kw were inverted by 2 tubes to 180 cycles alternating current without failure during a test which lasted for 50 hr. The water temperatures remained the same as in the last test.

Six similar tubes were also connected for 6-phase operation. The control for this test was likewise by means of a phase shifter, peaking transformers, and grid glow tubes. As yet no long time tests have been completed, but satisfactory operation of the circuit has been established, and the action of the polyphase inverter is shown by oscillograms reproduced in Figs. 6 and 7. In Fig. 6 the phenomenon is somewhat more complicated than the simple description given previously due to simultaneous conduction of current in more than 2 tubes. In general, however, the same negative kick occurs in the anode-cathode voltage.

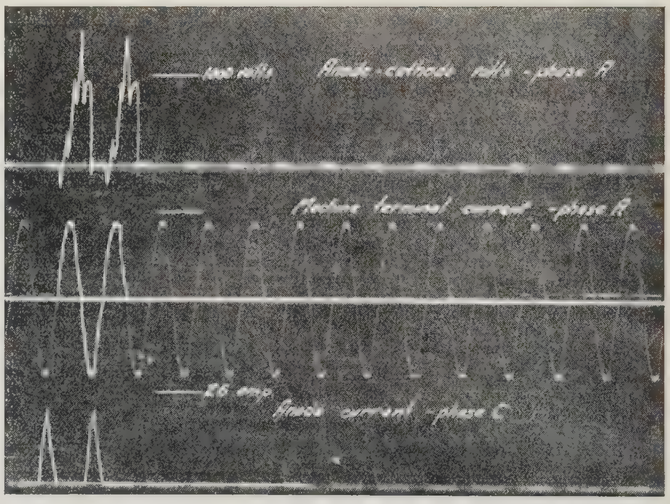


Fig. 7. Oscillogram of 6-phase inverter operation on a 500-volt d-c circuit with synchronous machine load. 178 cycles

In view of the small physical size of the ignitron and its low arc drop, the provisional rating as indicated by the tests seems to be sufficient to demonstrate the practical advantages of this type of tube.

Dielectric Properties of Cellulose Paper—I

Studies of the dielectric properties of pure cellulose paper as used for high voltage insulation are reported in this paper. The studies reported in Part I, presented herewith, include investigation of the dielectric loss, phase difference, and capacitance of paper insulated specimens as related to the moisture content of the paper. In Part II, which is scheduled for publication in a subsequent issue, these studies are extended to the variations in dielectric properties as related to temperature when the paper is extremely dry.

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Accurate engineering design of insulation for high voltage alternating current service is as yet not possible. The electrical characteristics of complex insulation can be predicted only approximately, from earlier measurements on the several constituents. This is particularly true of impregnated paper insulation such as used in high voltage cables. Aside from the uncertainty attaching to the changes in cable insulation in service and to the life of the insulation, almost equal uncertainty pertains to the final values in the assembled product of dielectric loss, power factor, and capacitance. As a simple example, it may be mentioned that the volumetric ratio of paper to oil in a cable, and measurements in advance of the separate properties of each, are not sufficient for the predetermination of either phase difference or capacitance in the assembled product.

In an earlier paper,[1] extensive studies of the relations between the basic physical and electrical properties of a number of oils and the subsequent properties of a single grade of paper as impregnated with the oils have been described. Various definite relationships were found. Among other things, it was shown that in the best grades of impregnated insulation, the properties of the paper before impregnation play a dominating part in fixing the properties of the assembled insulation. The paper, however, is far more complex and anomalous in its behavior than is a good oil. It therefore becomes of great interest to examine the properties of the paper itself and to determine if possible their bearing on the finished product. Several studies in this direction already have been reported.[2,8] In this paper is described a series of studies of loss, phase difference, and capacitance in a typical wood pulp paper, as related particularly to the moisture content and to temperature variation. From the results, the following conclusions have been reached:

1. Drying at a constant temperature 100 deg C produces stable conditions of moisture content and electrical properties. The values so found have been studied as related to evacuation pressures between 765 mm and 0.25 mm of mercury.

2. The studies permit quantitative determination of the amount of moisture present under different conditions and show that at 100 deg C, under final steady conditions, the moisture content at a pressure of 765 mm of mercury is 0.26 per cent, and at 0.25 mm is 0.05 per cent of the total volume of the sample. The moisture content at constant temperature varies closely as the $^1/_6$th power of the vacuum pressure.

3. Short-time d-c charge and discharge current curves, and a-c loss measurements have been used to determine the part played by moisture in affecting the values of the various electrical properties. Several interesting relationships have been found as follows:

(*a*) The total capacitance varies approximately as an exponential function of the moisture content.

(*b*) The component of total geometric capacitance attributable to occluded water varies directly with the moisture content.

(*c*) The component of capacitance due to dielectric absorption, the total power factor, and the absorption component of power factor all vary as exponential functions of the moisture content.

(*d*) The conduction component of power factor varies as exponential function of the moisture content only in the lower ranges, increasing thereafter more rapidly and no longer in simple relation.

4. At 100 deg C and 1 mm (of mercury) vacuum, high grade cable paper contained 0.07 per cent by volume of water. This water contributes substantially to the dielectric loss, the power factor, and the capacitance of the paper as measured before impregnation.

General Properties of Paper for Insulation

Although every effort is made to reduce the chemical and physical properties of the paper to those pertaining only to the cellulose of wood pulp fiber, nevertheless the electrical properties of the purest paper are not those commonly expected in a simple substance and the behavior of the best and purest paper is highly complex. The explanation is to be found in the fibrous structure of the paper which results first in a mesh-like combination of air and fiber, and second in a microscopic structure possessing the finest filaments and channels with consequent pronounced capillary properties. Such a structure is avidly absorbent of both gas and thin liquids such as water, and it is practically impossible to extract completely the air and moisture from the paper before impregnation. The anomalous properties of paper are to be ascribed principally to its moisture content. Under the best commercial methods, the electrical conductivity of dry paper is extremely small and difficult to measure. Nevertheless, under alternating stress it shows a definite dielectric loss and phase difference. These are due to the presence of dielectric absorption, in some way due to residual moisture. A similar influence is found on the ca-

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1. For all numbered references see list at end of paper.

pacitance which, when measured at 60 cycles, is noticeably greater than the geometric value.

The explanation of the dielectric absorption and loss in cable paper is not clear. Several explanations have been offered, as for example the layer theory of Maxwell, the capillary films of Evershed, the elongated filament of Dubois, the 3-layer dielectrics of Setoh and Toriama and of U. Meyer, and various pictures of the behavior of water ions adsorbed by the cellulose fiber, as for example, those of P. Böning and Murphy and Lowry. The Debye theory of polar molecules also has been invoked. None of these suggestions is as yet susceptible of experimental test because of inability to control and measure the submicroscopic processes involved. The case would be almost hopeless if reliance had to be placed on direct observation and measurement of moisture content and its distribution.

Fortunately, however, powerful indirect methods are now available. The short-time charge and discharge curves under continuous potential as observed in the amplifier oscillograph, by methods described in earlier papers, from the electrical engineering laboratory of The Johns Hopkins University, permit, through the von Schweidler method of analysis, the complete separation of the various constituents of all the electrical properties of a sample, and thereby through variation of experimental conditions to reach definite conclusions as to their origin. Now, the basic dielectric constant of cellulose fiber, the amounts of moisture present at various stages of dryness, and the contributions of such moisture to conductivity, absorption, dielectric constant, and loss are determined to close approximations.

Test Samples and Measurements

The test samples were made up in the form of cylindrical capacitors in which the high voltage electrode was a brass cylinder 61 cm long, 0.026 cm thick, and with outside diameter 6.35 cm. On this cylinder an uncalendered chemical wood pulp "kraft" paper 2.54 cm wide, and approximately 0.01 cm thick was spiralled cable fashion to a depth of 15 layers, each spiral making a butt joint and each layer having a registration of 0.63 cm. The outer electrode was of 0.04 cm sheet lead molded closely to the paper and bound down with a single layer of linen thread. The outer electrode was in 3 parts, one in the center being the measuring electrode, and a shorter one separated from the one in the center by a 0.02-cm gap, these 2 being used as guards. The lead electrodes were perforated with small holes at a spacing of 2.54 cm to aid in the drying process. For drying and temperature control, the sample was mounted within a tank having vacuum and electrical heating connections. A complete description of the tanks, method of heat control, various measuring and auxiliary connections have been given in an earlier paper.[3]

At atmospheric pressure cable paper absorbs large amounts of water, say from 5 to 10 per cent by volume. In this condition it shows high electric conduction and has no special interest as an insulator. A large proportion of this absorbed moisture may be driven off by raising the temperature to 80 deg C, but vacuum drying and higher temperatures are necessary in order to obtain the full insulating value. In the final condition the volume of water present is very small, but apparently it is distributed in adsorbed layers and capillary channels in such form as to render the paper highly anomalous in its electrical characteristics. Under continuous potential, polarization with a definite time element results in a behavior commonly described as dielectric absorption. Under alternating potential there are dielectric loss and increased capacitance due to dielectric absorption.

Direct measurement of the moisture content in the advanced stages of dryness is difficult. However, as will be shown, it is possible to compute the moisture content from electrical measurements taken on the paper when in stable condition at various evacuation pressures. In earlier work, it has been shown that at constant temperature and constant evacuation pressure, a stable condition as to conductivity and dielectric absorption is always reached. This indicates a condition of equilibrium as regards moisture content. Consequently, a standard drying temperature of 100 deg C has been adopted for all specimens and all measurements, with pressure as the only variable; the range of pressure studied was from 765 to 0.25 mm of mercury. The method also eliminates the important question of change of capacitance with temperature, of which a separate study has been made. Throughout the period at each pressure, electrical measurements were taken, tracing the effect of the progressive elimination of moisture and the arrival at the stationary condition pertaining to each pressure. For the taking of these measurements, the pressure was raised tempo-

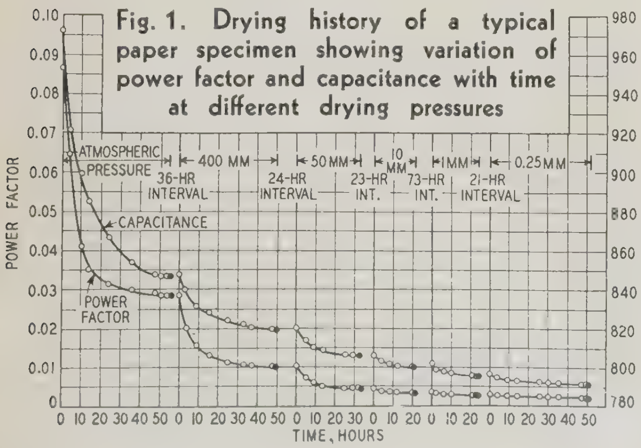


Fig. 1. Drying history of a typical paper specimen showing variation of power factor and capacitance with time at different drying pressures

(Left) All pressures expressed in millimeters of mercury. Temperature maintained constant at 100 deg C; frequency, 60 cycles

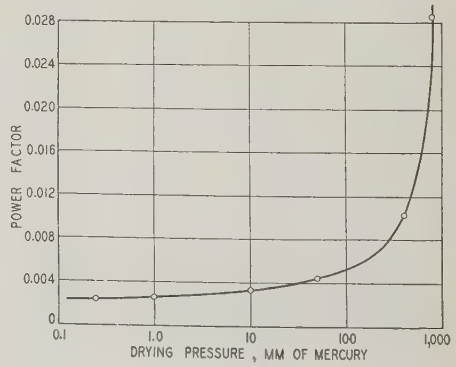


Fig. 2. (right). Variation of apparent power factor with drying pressure; 1,500 volts, 60 cycles

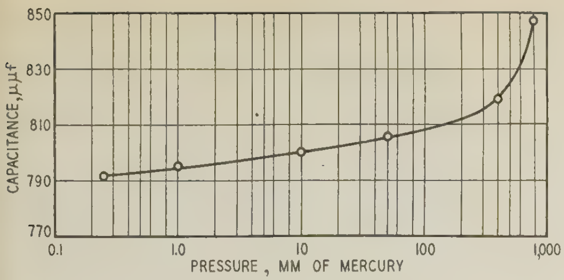


Fig. 3 (above). Variation of apparent capacitance with drying pressure; 1,500 volts, 60 cycles

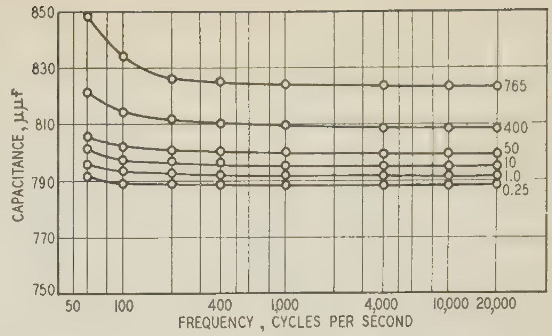


Fig. 4 (right). Variation of capacitance with frequency for different drying pressures

Numerical designations on curves indicate pressures in millimeters of mercury

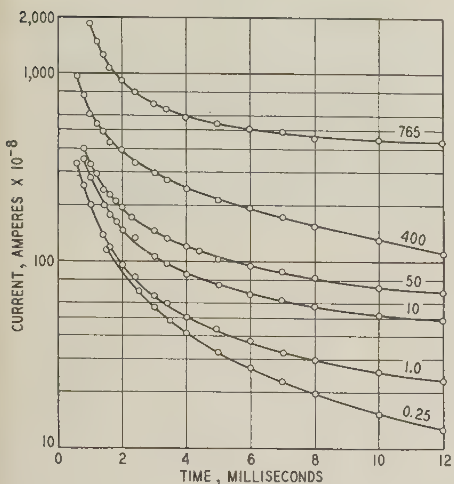


Fig. 5. Discharge curves (d-c) for various drying pressures

Numerical designations on curves indicate pressures in millimeters of mercury

rarily to that of the atmosphere by the admission of dry air. In this program 6 stages of dryness were investigated, the last one corresponding to an evacuation pressure of 0.25 mm. As may be seen, there appeared to be no reason why the evacuation should be carried to lower pressures.

The electrical measurements at each evacuation pressure were as follows:

1. *Frequency-Capacitance.* These measurements were made with a Hartley circuit oscillator of low harmonic content as source, and a shielded resistance capacitance Wien bridge, with 3-stage amplifier and d-c galvanometer as detector. The frequency range was from 60 to 40,000 cycles. The sensitivity was such that at 1,000 cycles and 70 volts bridge input, a difference of capacitance of 0.1μμf in 800 μμf could be detected.

2. *Phase Difference and Capacitance at 60 Cycles.* These were made with a high sensitivity Schering bridge with a-c galvanometer detector. The construction of the bridge, its operating characteristics and its sensitivity have been described in an earlier paper.[4] It has a capacitance sensitivity almost as great as that of the Wien bridge and a sensitivity for phase difference that is amply high (0.000005 power factor). As source, a 5-kva sine-wave generator was used.

3. *Dielectric Absorption.* A combination of amplifier and electromagnetic oscillograph with auxiliary rapid tripping circuit was used for the measurement of short time continuous current charge and discharge current curves.[5,6] The maximum sensitivity of this instrument is about 1.7×10^{-8} amp per millimeter deflection. It records a charge or discharge curve beginning 1 millisecond after the application of voltage or short circuit. As shown by Whitehead and Banos,[7] these curves may be used by the method of von Schweidler for the accurate computation of a-c loss and phase difference and the component of capacitance due to dielectric absorption.

4. *Long-Time Conductivity.* For charge and discharge current under continuous potential beyond 15 sec, a high sensitivity (3×10^{-12} amp per millimeter deflection) d'Arsonval galvanometer was used. Readings of final steady state current usually were taken after from 40 min to 1 hr.

The following properties of the dielectric sample are obtained from the foregoing measurements: (*a*) capacitance, dielectric constant, and phase difference at 60 cycles; (*b*) the geometric capacitance and the geometric dielectric constant; (*c*) the component of phase difference due to absorption; (*d*) the component of phase difference due to conduction; (*e*) the component of capacitance due to absorption; (*f*) the relaxation time of the dielectric; and (*g*) the steady state conductivity.

A general view of the results of progressive drying is shown in Fig. 1. Two series of curves are shown, one giving the variation of capacitance, the other that of phase difference at 60 cycles. As may be seen, these quantities change rapidly in the first stage (100 deg C at atmospheric pressure) because of the evaporation of moisture under temperature elevation only.[8] At the end of about 50 hr, the curves flatten out and reach approximately constant values. The succeeding steps of diminishing pressure all show initial decreases in both quantities, always leveling off into equilibrium. The final state of dryness studied was at a pressure of 0.25 mm of mercury; it may be seen that the phase difference and capacitance show no variation after 40 hr. The value of phase difference reached is extremely small. In this final condition some moisture is still present in the form of thin films or adsorbed layers, as is evidenced by the presence of dielectric absorption and loss. Further reduction of evacuation pressure undoubtedly would result in further reductions in phase difference and capacitance. However, it may be seen that the final values at each pressure are approaching approximately constant values. These final values, as shown later in the paper, may be deduced readily from the forms of the curves, and they permit the computation of the actual amount of water present at each state of dryness. The experimental points indicated by solid circles have been taken as representing the steady state as to moisture content, and the corresponding values have been used in the computations.

In Fig. 2 is shown the phase difference and in Fig. 3 the apparent capacitance at 60 cycles, each as function of the evacuation pressure. The capacitance frequency relation at various evacuation pressures is shown in Fig. 4. It should be noticed that the range up to 40,000 cycles is amply sufficient to determine the geometric capacitance at each pressure. In Fig. 5 is given the d-c discharge current in the interval 1 millisecond to 12 milliseconds for each evacuation pressure. These curves have been replotted from the corresponding oscillograms of which Fig. 6 shows a typical example. Even at the lowest pressure dielectric absorption is still present.

Discussion of Results

D-C A-C Correlation. Using the von Schweidler method, the curves of Fig. 5 may be used for computing the dielectric loss, the components of phase difference and of capacitance due to dielectric absorption, and the component of loss due to conduction, under alternating stress. The computations were made and the results compared with a-c measurements. Table I shows the results of this comparison. There is excellent agreement between computed and measured a-c values. Column 2 shows the phase difference as measured at 60 cycles, columns 3 and 4 the computed values due to absorption and conduction, respectively, and column 5 their sum. The agreement between columns 5 and 2 is well within the experimental error. Column 6 gives the capacitance at 60 cycles and column 7, the geometric capacitance determined by extrapolation to infinite frequency of the values given in Fig. 4. The differences between these 2 columns is given in column 8, which thus represents the component of capacitance arising in dielectric absorption. Column 9 gives the component of capacitance due to absorption as computed from the d-c discharge curve. Excellent agreement is seen also between columns 8 and 9.

Analysis of Phase Difference. The progressive variation of the separate components of the over-all phase difference at each pressure is shown in Fig. 7. The height of each block is the measured power factor at 60 cycles and its several components as measured and as computed are given on the same scale. At the left the phase difference in the driest condition is shown; it is very small and is accounted for entirely by dielectric absorption. No measurable short time conduction exists, and the long time conductivity is extremely small (2.0×10^{-17} mho per cm^3). The next block to the right represents a condition of slightly increased residual moisture. The original absorption has been increased by a small amount and a new component due to measurable conductivity has appeared. With further increase of moisture both absorption and conduction components increase, the rate of increase of the conduction being very rapid in the regions of higher residual moisture.

Analysis of Capacitance. The 60-cycle and geometric capacitances, each as function of the drying pressure, are shown in Fig. 8. Each decreases rapidly with pressure in the upper range, but below 10 mm, a linear relation to the logarithm of the pressure is indicated. The insert shows the lower pressure range with both coördinates linear and with extrapolated extensions (see later paragraphs.)

The excess of the 60-cycle capacitance over the geometric capacitance is attributed to dielectric absorption. (See Table I for agreement between computed and measured values.) The decrease in both geometric and 60-cycle capacitances with decreasing drying pressure results from the decrease in residual moisture. It has long been known that the further elimination of moisture reduces both conductivity and dielectric absorption in insulating materials. Figure 7 shows that at a pressure of 1.0 mm of mercury conduction practically has disappeared and the absorption component is very small. Conduction is not measurable at a pressure of 0.25 mm although absorption is still present. Figure 8 shows a corresponding decrease in the geometric capacitance which is simply because more and more moisture, with its high dielectric constant, is being withdrawn. The geometric capacitance containing no absorption component is a composite value due to a mixture of 3 substances, fiber, air, and moisture, their dielectric constants, and their volumetric proportions and arrangement. Were it possible completely to remove all moisture, the paper would show no absorption, zero power factor, and 60-cycle capacitance equal to the geometric value. The pure cellulose air structure would show no anomalies, but only the property of dielectric constant. Up to this time, however, it has not been found possible to remove *all* the moisture and so reach this ideal condition.

Computation of Moisture Content. The nature of the mechanism by which moisture causes dielectric absorption is not known. Conducting filaments or layers would suggest the mixture theory of Maxwell. Murphy and Lowry and P. Böning have presented pictures of the adsorption of layers of moisture on the capillary walls of the cellulose tissue; this picture makes a stronger appeal in the advanced stages of dryness of the present studies. Obviously, with more moisture present and with possible traces of impurities, it is possible to picture limited conducting paths increasing both conduction and absorption components more in accordance with the Maxwell picture. In the present studies, the treatment at a pressure of 0.25 mm of mercury represents the best condition of dryness obtained. It is evident that some absorption is still present with components of power factor and of capacitance due to absorption, these components being a function of the amount of moisture present.

Table I—Analysis of Power Factor and Capacitance of Paper Samples Versus Drying Pressure

1	2	3	4	5	6	7	8	9
	Power Factor				Capacitance, $\mu\mu f$			
		D-C Short-Time Analysis						
Pressure, In. of Mercury	60-Cycle Bridge Measurement	Absorption	Conduction	Abs. + Cond.	60-Cycle Bridge Measurements C	Geometric Capacitance (∞ frequency) C_∞	Absorption Capacitance $C - C_\infty$ or ΔC_r	D-C Analysis Absorption Capacitance ΔC_r
0.25	0.002255	0.00221		0.00221	791.5	788.5	3.0	2.9
1.0	0.002599	0.00246	0.000233	0.002685	795.3	791.7	3.6	3.43
10 0	0.003314	0.003114	0.000254	0.003370	800.0	795.1	4.9	4.3
50.0	0.004394	0.0040	0.000483	0.004495	805.5	799.6	5.9	5.01
400.0	0.01021	0.00938	0.000906	0.010296	819.0	808.5	10.5	10.6
765.0	0.02865	0.02045	0.00930	0.02995	847.0	823.1	23.9	23.

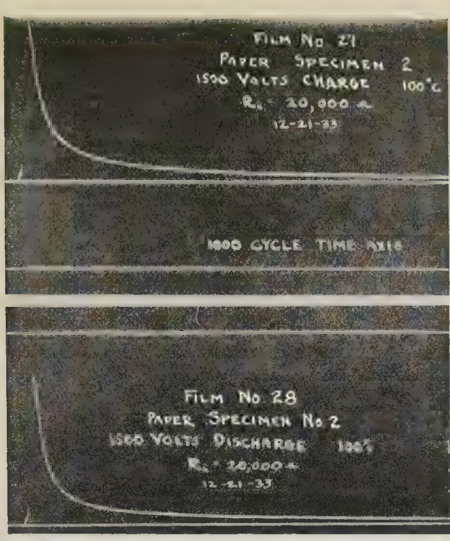
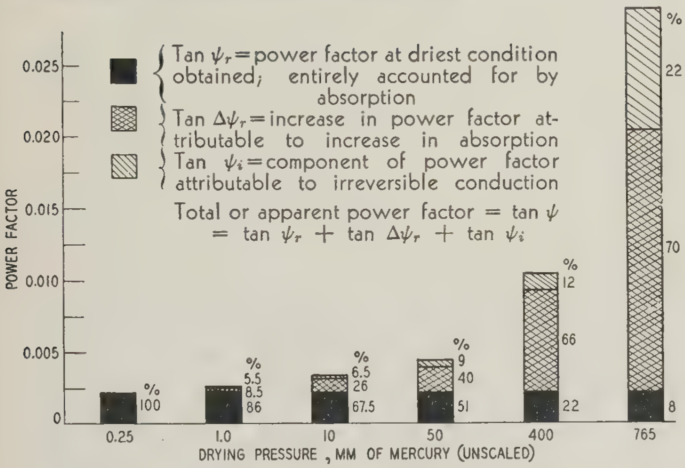


Fig. 6. Typical d-c charge and discharge current oscillograms of a well dried paper specimen

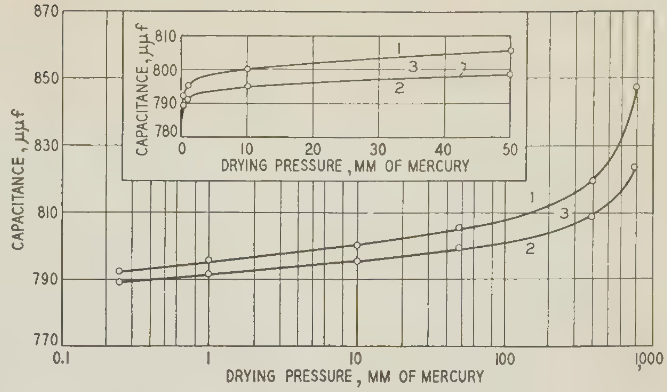
Fig. 8 (right). Variation of components of capacitance with drying pressure

Fig. 7 (below). Analysis of power factor at various stages of dryness



From Fig. 8 it may be seen that both apparent (i. e., measured) and geometric capacitance decrease continually with decreasing pressure. The former decreases more rapidly. The point of intersection of the 2 curves if obtainable would mark the condition of zero absorption component of capacitance, and presumably of zero moisture content; conductivity has disappeared at much higher pressures, and at this point absorption also disappears. The apparent and geometric capacitances have the same value, which is that of the perfectly dry paper fiber plus air. If this value is known, the moisture content at various pressures can be computed and other interesting deductions may be made, all as based upon the electrical measurements.

The semilogarithmic curves of Fig. 8 invite extrapolation for the determination of their point of intersection. They have approximately zero curvature below 10-mm pressure, thus permitting a high degree of accuracy in graphical extrapolation. The 2 curves so extended must intersect in the neighborhood of 10^{-4} mm pressure and 780 $\mu\mu$f capacitance. The point of intersection also was determined by well-known methods of analytical geometry using the slopes of the curves at 1-mm and 0.25-mm pressures. This computation gave a value of 780.6 $\mu\mu$f for the capacitance at the point of intersection. As a further check, the values of ΔC_r (the component of capacitance due to absorption, i. e., the difference between the ordinates of the



Curve 1. 60-cycle apparent capacitance
Curve 2. 40,000-cycle capacitance (equivalent to geometric capacitance)
3. Component of capacitance attributable to absorption

2 curves of Fig. 8) were plotted against the pressure and the curve extrapolated to zero capacitance. The curve is accurately exponential below 60-mm pressure and indicates zero value for ΔC_r at a pressure of 9.5×10^{-5} mm of mercury, corresponding closely with that determined by the first method.

The insert in Fig. 8 shows the capacitance-pressure relations in the lower range as plotted in linear coordinates. The experimental points at 0.25-mm and 1.0-mm pressures are shown, those at higher pressures not appearing. It may be seen that below 1.0 mm the curve begins a definite change of curvature downward. The fact that this change takes place in accordance with the uniform decrease of curvature of the semilogarithmic curve, is strong indication that the law of the change continues to lower pressures and that the values obtained from the extrapolation are closely accurate. In the insert the experimental curves have been continued below 0.25-mm pressure to intersections at 780 $\mu\mu$f and in the neighborhood of zero pressure. The mean of the 2 extrapolated values of the capacitance of the moisture-free paper is 780.3 $\mu\mu$f, and this is the value used in computing the moisture content of the paper at various pressures.

Knowing the value of the capacitance of dry fiber plus air, it is possible to compute also the probable minimum moisture content of the specimen in per cent of the total volume for each drying pressure under equilibrium conditions. This value is given by

$$M = 100\,\frac{C_\infty - C_o}{K_w - 1}\cdot\frac{K_\infty}{C_\infty}$$

where

M = minimum moisture content in per cent of total volume
C_∞ = geometric capacitance of paper sample as measured
K_∞ = geometric dielectric constant of paper sample corresponding to C_∞
C_o = geometric capacitance of dry fiber and air (taken as 780.3 $\mu\mu$f)
K_w = geometrical dielectric constant of water

The question of the dielectric constant of water, K_w, arises. A review of the literature[9,10,11] as related to temperature and the thin layer state, has led to the selection of a value of 48 as most probable for the conditions of this study. In this manner, the moisture content in per cent of total volume of the specimen as between electrodes was computed

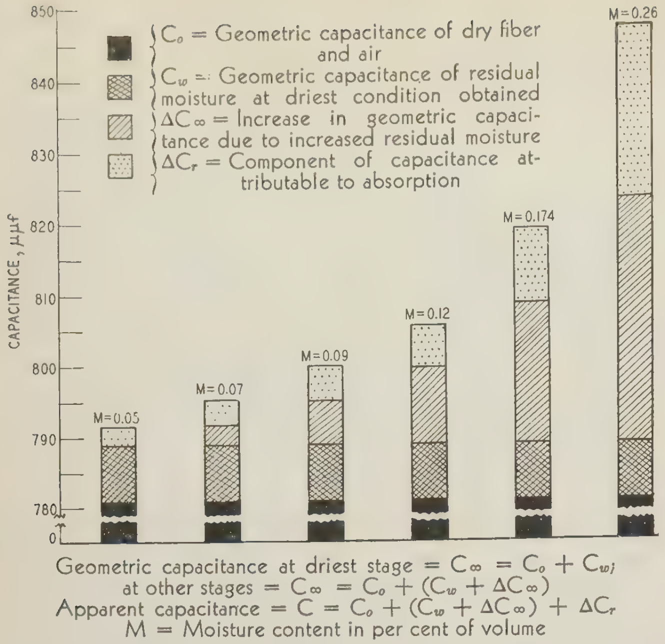


Fig. 10. Residual moisture content as a function of drying pressure

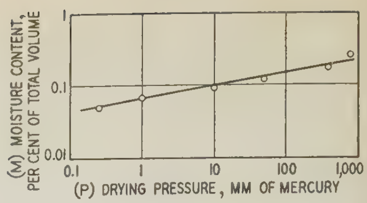


Fig. 9 (left). Analysis of capacitance at various stages of dryness

Fig. 11. Variation of components of power factor with residual moisture content

Tan ψ = apparent power factor
Tan ψ_r = absorption component
Tan ψ_l = conduction component

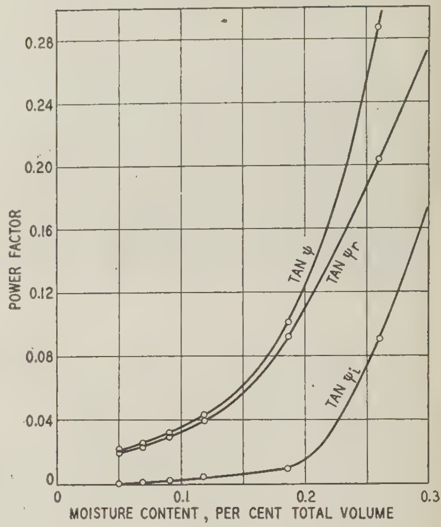


Table II—Data on Computation of Minimum Moisture Content

P Mm Hg	C_∞ $\mu\mu f$	K_∞	K_w	C_o $\mu\mu f$	M Per Cent
0.25	788.6	2.375	48	780.3	0.05
1.0	791.7	2.382	48	780.3	0.07
10.0	795.1	2.395	48	780.3	0.09
50.0	799.6	2.406	48	780.3	0.12
400.0	808.5	2.435	48	780.3	0.175
765.0	823.1	2.478	48	780.3	0.26

P = drying pressure in millimeters of mercury
C_∞ = total geometric capacitance of composite paper
K_∞ = geometric dielectric constant of composite paper (corresponding to C_∞)
K_w = dielectric constant of adsorbed water
C_o = geometric capacitance of dry fiber-air structure
M = minimum moisture content in per cent of total volume

for each state of drying pressure. Table II shows the values of the various components of the apparent capacitance and the resulting computed residual moisture in per cent of specimen volume. It may be seen that the range of moisture content was very narrow; the ratio between atmospheric pressure and 0.25 mm of mercury, both at 100 deg C, is about 5 to 1. (Also see Fig. 10.)

Influence of Residual Moisture on Capacitance. Analysis of the apparent capacitance of the paper at 60 cycles for different conditions of dryness is shown in Fig. 9. Starting with the driest condition the apparent capacitance is made up of 3 components. The solid portion is the geometric capacitance of the fiber and air alone computed from the results of Fig. 8 as already described. The cross-hatched portion is the geometric capacitance of the residual moisture in the driest condition studied. The hatched portion is the addition to the geometric capacitance brought about by increased residual moisture. The dotted portion is the component of the capacitance arising in dielectric absorption, that is, due to the polarizing properties of the adsorbed layers of residual moisture. In all cases the total capacitance of the paper is made up almost entirely of the composite fiber and air. However, it may be seen that for 0.26-per cent moisture content, the geometric capacitance of this occluded moisture plus the capacitance component due to absorption may amount to as much as 8 per cent of the total apparent capacitance.

Relation of Moisture Content to Pressure. If the moisture content be plotted as a function of the drying pressure in double logarithmic coördinates, the result is a straight line, as shown in Fig. 10. Accordingly, the moisture content, as function of the drying pressure, may be expressed as $M = KP^n$, where M is the moisture content, P the drying pressure, and K and n constants. If M be expressed in per cent of total volume and P in mm of mercury, $M = 0.068P^{1/6}$; it should be remembered that this relation holds only for the constant drying temperature of 100 deg C and with final steady conditions under the various values of pressure. No obvious reason has suggested itself for the apparently simple relation here found.

Power Factor Moisture Relation. Variation of the power factor with moisture content is shown in Fig. 11. The absorption component increases rapidly, and so also does the conduction component beyond 0.18-per cent moisture content. The apparent power factor is thus very sensitive to slight residual moisture changes, and particularly so at the higher values. Taking into account the whole range studied, there is an increase of 15 times in power factor as against a corresponding increase of 5 times in residual moisture content. Absorption contributes the greater proportion of this increase.

In Figs. 12 and 13, the power factor and its components are plotted as functions of the residual moisture in semilogarithmic coördinates. It is interesting to note that both the total power factor and the absorption component of the power factor vary in exponential relation to the moisture con-

tent, and so the variation for each may be expressed by the equation $\tan \psi = Ke^{\alpha M}$ where $\tan \psi$ is the power factor, M the per cent of moisture content, and K and α constants. The component of power factor due to conduction appears to follow a similar relation for small values of moisture, but departs therefrom above 0.2-per cent moisture content.

Capacitance-Moisture Relation. In Fig. 14 the apparent capacitance with its several components are plotted against moisture content in semilogarithmic coördinates. Curve C gives the total capacitance as measured at 60 cycles. Curve C_o gives the geometric capacitance of the composite pure fiber plus air, which obviously does not vary with moisture content. The geometric capacitance of the occluded moisture is shown in curve C_w, and the component of capacitance due to dielectric absorption in curve ΔC_r. The geometric capacitance of the residual moisture is obviously a simple linear function of the moisture content. However, it may be seen that the component due to absorption, like that of the corresponding component of power factor, follows an exponential relation to the moisture content as shown by $\Delta C_r = Ce^{bM}$.

Theoretical Discussion

If an attempt be made to picture the mechanism by which the absorption of moisture affects the phenomena of absorption and conduction, the procedure might be somewhat as follows: When entirely free of moisture and soluble impurities, the paper consists of a structure of pure cellulose with interspersed air spaces, this structure being free under electric stress from both conduction and energy loss. Electrically, the paper then shows only the property of dielectric constant, which should vary only in the classical Clausius-Mosotti manner. The addition of water naturally introduces ionic conduction. For relatively small moisture content the moisture probably exists in the form of adsorbed layers over the fiber structure and possibly in capillary channels. Few if any continuous ionic paths exist that are continuous through the insulation wall, and conduction, if present at all, must be very small. However, in accordance with the mechanism of an adsorbed ionic system, as set forth bý Polyani, Gouy, and Eucken and extended to the dielectric case by Murphy and Lowry, the dielectric now shows the phenomenon of dielectric absorption with consequent absorption of energy under alternating stress. The picture here is that the adsorbed ions either move in limited paths or undergo elastic displacement under the action of the field. Obviously, the phenomena might be explained equally well in accordance with the Maxwell picture of a dielectric, made up of components having different values of conductivity and dielectric constant. In either event an equivalent resistance-capacitance picture, as proposed by Murphy and Lowry,[12] may be set up, representing the over-all behavior of the dielectric. For small values of moisture, conduction is absent or negligible, and dielectric loss is entirely due to reversible dielectric absorption. Increased residual moisture increases the geometric capacitance and also changes the form of the relaxation function characteristic of reversible absorption. The nature of this change is the addition of a slow decaying element of reversible absorption, due to increased thickness of adsorbed water films. Furthermore, increased residual moisture soon increases the number of through ionic paths from electrode to electrode, and so causes a measurable value of irreversible conduction current under continuous potential. This component of the current increases very rapidly with further addition of moisture, and for moisture contents of more than 0.5 to 1 per cent it may predominate over the other elements of the observed loss.

It is surprising to find the simple relationships between moisture content and electrical properties indicated in this study. While as yet no obvious

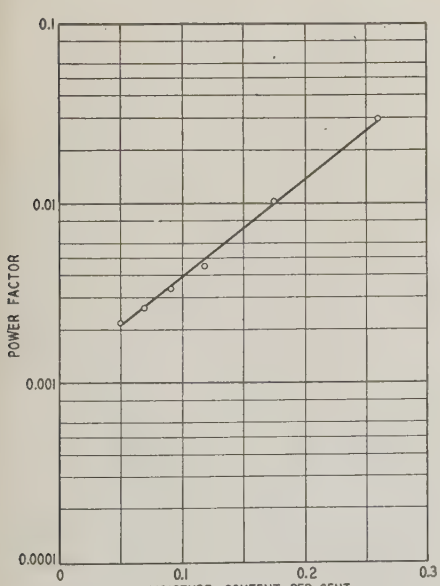


Fig. 12. Apparent power factor versus moisture content

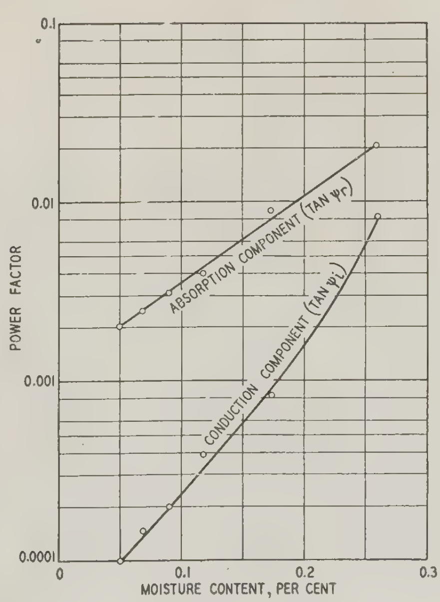


Fig. 13. Components of power factor versus moisture content

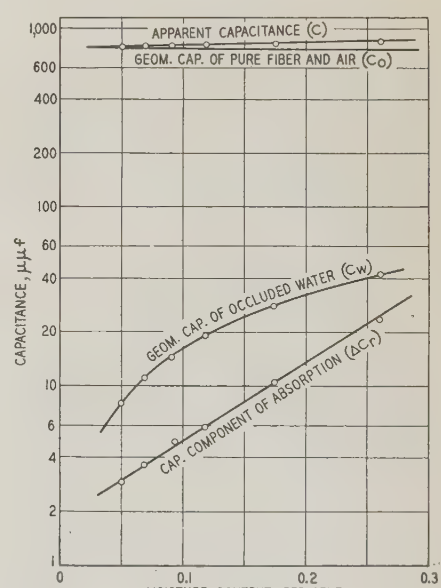


Fig. 14. Components of capacitance versus moisture content

explanations have suggested themselves, these simple relationships seem to indicate clearly that the phenomenon of adsorption of moisture by the fibrous materials commonly used in insulation is much more regular than heretofore supposed.

In these studies and in others conducted in the electrical engineering laboratory at The Johns Hopkins University in this field, the aim has been to determine the ultimate basic electrical properties of impregnated paper insulation without special reference to the question of whether full utilization can be made of these properties under various limitations imposed by the methods of manufacture for the cable trade. Obviously, it is important to know these ultimate properties if the value attaching to possible alterations or improvements in the methods of manufacture are to be ascertained. The results of the studies reported in this paper seem to bear more directly than usual upon methods of manufacture, since they give information as to the amount of moisture contained in a standard grade of wood pulp paper. It is found, for example, that at 100 deg C and 10-mm, 1-mm, and 0.25-mm (of mercury) pressures, the moisture contents of the paper are 0.09, 0.07, 0.05 per cent by volume, respectively. The reduction of moisture by decreasing the pressure is very much less rapid in the lower than in the upper ranges. Obviously, still further reduction of moisture may be accomplished by elevation to higher temperatures. It commonly is understood, however, that at any temperature the paper itself will stand without destruction, it still will retain a certain proportion of moisture.

In an earlier paper the influence of the original conducting properties of various impregnating oils on the electrical properties of the impregnated product have been traced. It was shown that by far the larger component of the dielectric losses is due to the paper. A reduction of these losses therefore would be reflected as a reduction in the total losses for any type of impregnating oil. Furthermore, an intimate relationship has been shown to exist between the properties of the oil and the dielectric strength and probable life of the impregnated insulation.[13] It appears very probable that these relationships must be dependent on the amount of moisture originally in the paper. It may be well to repeat that all statements as to electrical properties, dielectric strength, and life of insulation, as made in these papers, refer to the inherent properties of impregnated paper and assume complete impregnation and the absence of gas voids such as commonly cause a rise in the power factor-voltage curve.

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Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

Voltage Control of Vapor Rectifiers

Discussion and author's closure of a paper by Didier Journeaux published in the June 1934 issue, p. 976–88, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

R. E. Hellmund: The analytical studies presented by Messrs. Journeaux and Herskind in their papers on controlled rectifiers appear to be quite timely. In a discussion presented at the last summer convention, I pointed out that of the various electronic devices the pool-type rectifier and its modifications hold the greatest promise in all future applications involving appreciable amounts of power and especially large currents. The papers presented and the great amount of work evidenced by the material given seem to indicate increasing appreciation of the future possibilities of the pool-type device for various purposes requiring control features. In saying that the papers are quite timely, I do so with the idea that it is the engineer's function to concern himself with and to vision future possibilities even though the chances of immediate practical application are not particularly good. However, since it is also the engineer's function to study the economic aspects as applying to the immediate future, a brief review of the various devices and their applications from this point of view may be justified.

As is generally known, the straight mercury-pool rectifier is already with us as a thoroughly practicable, reliable, and economically competitive device for converting alternating current into direct current. It has occupied this position for some time for voltages of 600 and above, and more particularly in its application to railway substations. With the progress made during recent years in lowering the losses in the rectifier through refinements in design, such as the sectionalized construction and the use of the igniter principle, the way has been paved for extending the economical application of rectifiers to lower voltages such as

encountered in electrochemical work and possibly lower voltage d-c systems.

As pointed out in the 2 papers, the addition of the grid control or similar arrangements for the purpose of voltage control brings with it problems relating to power factor and interference, and the greater the range of voltage regulation the more troublesome these problems become. Various technical means are known or can be devised for taking care of these problems. One of the papers suggests a combined transformer tap and grid control to improve the power factor when large voltage variations are required. In a patent issued January 15, 1924 (No. 1,480,722), I suggested the use of a synchronous machine floating across the a-c terminals for the combined purpose of power-factor correction and interference elimination. Static condensers and stationary filtering equipment also can be used for these purposes. Another possibility has been brought out in Mr. Ludwig's discussion. All of this, however, means extra expense and complications, and in a great many cases where wider ranges of voltage regulation are required it results in conditions making the application of the rectifier uneconomical and noncompetitive with other means accomplishing similar results. On the other hand, the controlled rectifier may find fairly extensive application in some special fields where there are no competitive devices accomplishing the same results; the most outstanding example of this is the use of the ignitron in connection with spot and seam welding in cases where the mechanical control of the welder does not work out satisfactorily.

The prospects of extensive early application of the mercury-pool device as inverter or frequency changer, or of combinations of these devices and rectifiers seem to be even less promising. While the papers make little mention of experimental work along these latter lines, such work is being carried on in various places, and, as a matter of fact, inverters of the ignitron type have been very successfully operated over extended periods in connection with adjustable-speed motors at the Westinghouse laboratories in East Pittsburgh. However, this fact in itself, while demonstrating the workability of such schemes, does not prove that they are justified economically under present conditions. This question can be answered only by a study of the various possibilities of their application in comparison with other means for accomplishing the same results.

A good deal of attention has, for instance, been given at various times to the use of rectifiers and inverters for d-c power transmission. However, very careful and extensive studies of the economics of transmission indicate that d-c transmission of the type mentioned shows economic possibilities only in special cases where considerable amounts of power have to be transmitted over very long distances, or perhaps in a few cases where extensive use of cables has to be made in power transmission. Applications of the latter kind are exceedingly rare and limited to a few metropolitan districts. In water power projects involving large amounts of power and long distance transmission, it is very common that the sources of the water power are distributed over different localities, and in addition there are usually many points of power utilization. In these projects the number of rectifier and inverter stations and their incident cost is so great that the use of direct current cannot compete with the ordinary a-c systems at the present stage of the art.

Discussions in This Issue

On these and the following 25 pages appear discussions of technical papers presented during the sessions on electrical machinery and education of the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. All discussions received in complete and acceptable form at Institute headquarters within 2 weeks after the convention, and subsequently reviewed by the technical committees and recommended for publication, are included. Authors' closures, where they have been submitted, will be found at the ends of the discussions on their respective papers.

Another application of rectifiers or inverters, or both, which has received considerable attention over an extended period of time is that of speed control of motors, outstanding among these being the application to railway work. Ever since the first experimental operation of rectifiers on a motor car of the New York, New Haven, and Hartford Railroad over 20 years ago, numerous rectifier and inverter schemes have been discussed in technical literature and considerable progress in the improvement of these schemes has been made. However, during the same period other types of apparatus for railway work, as, for instance, the single-phase commutator motor, also have been continuously and appreciably improved. As a consequence, arrangements with electronic devices have not during this entire period reached the point where they could compete with other possibilities for operating cars or locomotives.

The same might be said of motor applications in industry. While the problem of devising adjustable-speed motors has been before electrical engineers ever since the more general use of alternating current, and though the use of electronic devices for this purpose has been given repeated consideration and study, they are still not quite competitive with other solutions of the problem. Furthermore, the total number of adjustable-speed motor applications in industry for which the mercury-pool rectifier could be considered is after all not very great, and because of this rather small total demand and the various competitive schemes able to fill a large part of such demand, the use of the mercury-pool device for motor control in industry undoubtedly will be limited to a few very special cases for a long time to come.

Electronic devices have also been considered in connection with ship propulsion, and here again it would seem that their use can hardly be justified economically except perhaps in very special cases.

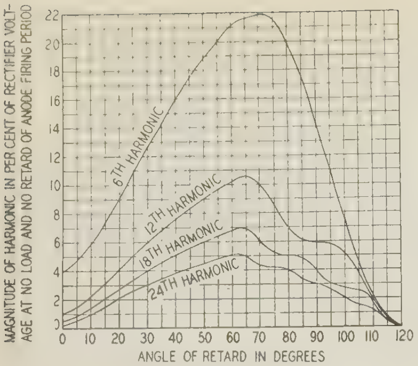
One of the papers makes mention of a need for inverter operation of substations for d-c railways, and of course a similar condition may be met in large d-c operated buildings where there may be occasional inverse power from the operation of elevators. It is quite evident that the regenerative arrangements discussed in Mr. Herskind's paper entail appreciable complication and expense. Since the amount of regenerated power in both of the applications mentioned is usually of small magnitude and occurring only for short periods, it probably can be taken care of to best advantage by dissipating the power in a resistance or by the use of batteries in the case of a building. With railways operating induction machines on locomotives, it is common practice to use resistances for dissipating regenerative energy. For this reason I do not believe that early use will be made of inverter operation either in railway substations or in large buildings.

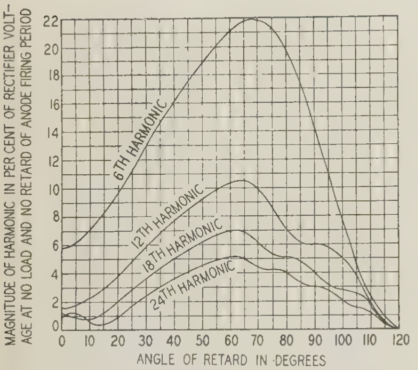
From the previous discussion of the specific application possibilities, it seems quite evident that for some years to come there will be very little practical application of the mercury-pool device for anything except rectification. This, however, should not be surprising, because it is quite common that considerable time elapses between the conception of certain ideas and their practical and economical application. An illustration of this is the mercury-arc rectifier itself, the more general application of which has been very slow in materializing; it is only now, more than 20 years after the first field trials of rectifiers, that its application to lower voltages is becoming economical for larger amounts of energy.

Nevertheless, the practical and operating engineer undoubtedly wishes to keep informed on developments such as described in the papers because some of them may become of practical importance in the future. The immediate interest of the operating engineer should, however, be directed toward expanding the applications of the rectifier which are now becoming economical, such as low-voltage applications and some special applications to welding and similar processes. This will greatly assist further progress because it will lead toward reduced costs and further perfection in performance of the mercury-pool device and its various auxiliaries. These factors in turn are the principal prerequisites for extending the economically justified applications of the devices and therefore should command the principal attention of both the operators and the manufacturers.

It should be appreciated in this connection that it is difficult for new devices, even though they possess inherent merits, to compete with older devices which have had the benefit of many years of development and continuous improvement. The rectifier art is still new and we are still far from the fundamental limits of size, cost, and efficiency—all factors of determining importance in economic considerations. Therefore, if more extensive use of rectifiers where they are now competitive paves the way for improvements of these various factors, some projects which are now uneconomical will become justified in the future.

F. O. Stebbins: In Figs. 10, 11, and 12 of this paper the author presents some excellent curves showing the relations between the 3 lower orders of harmonics present in the output voltage of grid controlled recti-





Figs. 1 (top) and 2 (bottom). Curves showing the 4 lower orders of harmonics for a 6-phase controlled rectifier: (1) at light load supplying a noninductive d-c load; (2) at approximately full load supplying a noninductive d-c load

fiers and the d-c load as represented by the factor KX_w, when the d-c load is highly inductive and the angle of retard is small. He does not attempt to discuss these same harmonics when the d-c load is noninductive, and the following discussion of output voltage wave shape will be confined to this type of load.

The continuous voltage wave shape depends upon the angle of retard and the angle of overlap. In a given rectifier developing a constant value of continuous voltage the angles of retard and overlap will be different when the d-c load is highly inductive than when the d-c load is noninductive. The output voltage wave shape and magnitudes of harmonics will therefore be different for these 2 cases.

If P' represents the total number of transformer secondary phases, it can be shown that for noninductive d-c loads when the angle of retard is greater than $\frac{\pi}{2} = \frac{\pi}{P'}$, there is no overlapping and the angle of overlap is zero. For 6 phase and 12 phase rectifiers the values of $\frac{\pi}{2} - \frac{\pi}{P'}$ are 60 and 75 deg, respectively.

If it is assumed that during commutation the load current is flat, but that at all other times it is proportional to the continuous voltage, formulas for the angles of retard and of overlap can be developed in terms of the continuous load current which are approximately correct. By substituting these values of retard and overlap in formulas 26 and 27 of the paper, the magnitudes of the harmonics in the continuous voltage can be calculated for rectifiers with and without interphase transformers when the angle of retard is less than $\frac{\pi}{2} - \frac{\pi}{P'}$.

For rectifiers without interphase transformers and angles of retard greater than $\frac{\pi}{2} - \frac{\pi}{P'}$, a new analysis of the output voltage must be made in order to calculate the wave shape. For rectifiers with interphase transformers there is considerable difference of opinion as to just what takes place when the angle of retard is greater than $\frac{\pi}{2} - \frac{\pi}{P'}$. The author presents a clear and concise description of this phenomenon in a 6-phase rectifier with interphase transformer when certain conditions are assumed. It is my belief, however, that the author's assumptions regarding the behavior of the interphase transformer do not hold true in all cases. Does the author have experimental evidence which justifies his assumptions? For rectifiers having interphase transformers my discussion is confined to the output voltage wave shape obtained with angles of retard less than $\frac{\pi}{2} - \frac{\pi}{P'}$.

Figures 1 and 2 of this discussion show the 4 lower orders of harmonics present in the output voltage at light load and approximate full load for a particular 6-phase rectifier without interphase transformer. These 2 figures also apply to a particular 6-phase rectifier with interphase transformer for angles of retard of less than $\frac{\pi}{2} - \frac{\pi}{P'}$ or 60 deg.

C. W. Frick: One of the features of the controlled-voltage rectifier which is of interest is the wave shape of the output voltage. Figures 10, 11, and 12 of the paper give the percentage values of the 6th, 12th, and 18th harmonics when the angle of delay X_0 and the factor KX_W are known. Equations 15 and 17 show that the factor KX_W is equal to $\frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}}$ which in many cases may be easier to evaluate than X_W. It also shows that the abscissas of the curves are proportional to the load in any given set-up. It may be of interest to show how to evaluate the expression $\frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}}$ when there are interphase transformers. Since commutation then takes place between anodes in the same group, I must be taken as the load direct current in each group and p the number of phases in the group. The proper value of commutating reactance for the connection considered must be used. For the benefit of those who wish to evaluate X_W from the circuit constants, it is suggested that the author give definitions of I_p, E_p and X_p. These definitions are needed to determine the factor K for any particular connection. The paper gives a value of K for "the 12-phase interphase transformer connection." Twelve-phase operation can be obtained with several arrangements of interphase transformers, for instance 4 groups of 3 phases or 2 groups of 6 phases. The connection or connections to which the given value of K applies should be stated.

The curves show values of the harmonics plotted against the factor KX_W for various values of the angle of delay, also called the angle of retard. Generally it is the output voltage obtained by grid control rather than the angle of delay which is of interest. In order to use the curves when the output voltage is given it is necessary to refer to equations in the paper to obtain the angle of delay. By making use of the relation between the output voltage, angle of delay, and the factor $\frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}}$ the values of the harmonics can be plotted against the last factor for various values of output voltage as a percentage of the output voltage without grid control. These curves make it unnecessary to calculate either the angle of delay or the angle of overlap. A set of curves for the 6th, 12th, 18th, and 24th harmonics has been incorporated in a paper by F. O. Stebbins and myself, which has been accepted by the A.I.E.E. for publication. (September 1934 issue, p. 1259–65.)

The author suggests that the 6th and 18th harmonics which are theoretically zero in the 12-phase rectifier but are actually present in small amounts may vary in accordance with the curves on Figs. 10 and 12, read with larger scales of ordinates. This assumption does not seem justifiable in all cases. There are several causes besides unequal division of load between 2 sets of 6 phases which may cause these harmonics to appear in the 12-phase rectifier. In some cases the cause may be the presence of corresponding odd harmonics in the voltage on the a-c side and the 6th or 18th harmonic on the d-c side should be practically constant provided the a-c voltage wave shape remains the same.

The example chosen to illustrate the TIF (telephone interference factor) shows principally the effect of grid control at light load. It does not show the effect of adjusting the voltage at normal load by grid control. It would be of interest if the author also would show in the same example the TIF obtained when the voltage at normal load is adjusted 5 per cent with grid control. The formula (eq 35) for the TIF when the voltage is not regulated does not include the effects on the output voltage of arc drop and losses in the rectifier transformer, although these effects were allowed for in calculating the TIF with regulated voltage. This has only a small effect on the TIF values in the example considered. It appears that X_W is expressed decimally when used in eq 35 although eq 16 gives it as a percentage.

C. C. Herskind: Mr. Journeaux's paper presents a very thorough analysis of the characteristics of the mercury arc rectifier when operating with grid control. It covers the operation of the rectifier with inductive, resistive, and counter emf loads. The curves of Fig. 5 showing the output voltage wave shapes as the voltage is reduced by retarding the grids should be particularly noted, as they give an excellent physical conception of the effect of grid control upon the rectifier characteristics. The only thing Mr. Journeaux appears to have omitted is the difficult subject of harmonics on the a-c side of the rectifier.

In connection with the voltage regulation

characteristics shown in Fig. 9 of the paper, I wish to point out that these curves, as well as similar curves in the writer's own paper, apply only as long as the commutation period is so short that one commutation is completed before the next one is begun. For example, if the commutation period in a 6-phase diametrical circuit is so long that 2 anodes fire all the time, then the output voltage will be less than that shown by the regulation curves. This condition arises only at the higher overloads in the usual rectifier.

I wish to call attention to the load scale used in plotting the regulation curves and harmonic components of the output voltage. This load factor is denoted by the symbol KX_W where K is a coefficient whose value depends upon the type of circuit and X_W is the working reactance. The value of this factor is the same as that of the load factor IX used in the writer's own paper if the latter factor E_0 is multiplied by $\frac{1}{\sin\frac{\pi}{p}}$.

The use of these load factors facilitates comparison of the different circuits. Of these 2 factors, the form $\frac{IX}{E_0}$ seems to be more desirable as it is more generally applicable, does not involve the calculation of the factor K, and gives a better physical conception of the relations involved.

The factor K cannot be calculated directly for all connections by substitution in the formula given in the paper (eq 18). Also, it does not indicate the relative effect of primary line reactance and commutating reactance. The effect of primary reactance depends upon the type of connection, for example, in the 6-phase diametric connection the commutating reactance is equal to the phase reactance, in the 6-phase forked connection the commutating reactance is $^1/_3$ of the phase reactance, and in other circuits different ratios are obtained.

When the load factor KX_W is used, the variation in load current is represented as a variation in working reactance. In an actual circuit the reactance remains constant while the current varies. This is represented physically if the load factor $\frac{IX}{E_0}$ is used. In some cases involving the solution of circuits containing capacitance as well as inductance the factor $\frac{IX}{E_0}$ has been further extended to the form $\frac{I\sqrt{\frac{L}{C}}}{E_0}$ where $\sqrt{\frac{L}{C}}$ is the impedance of the commutating circuit.

L. R. Ludwig: The last section of this paper raises several questions whose answers do not seem to be entirely clear. If the text has been correctly understood, the proposal is made to reduce the output voltage of a rectifier by both starting and stopping each anode at instants earlier in time than the normal transition points in the case of the uncontrolled rectifier. If this is done, the fundamental of the current wave in each phase would lead the voltage of that phase, and at first sight a considerable improvement would result. In other words, leading reactive power is to be drawn from the line by virtue of repeated switching operations.

The rectifier and transformer are analogous to a commutator machine, in which the alternating currents generated in or supplied to the armature are rectified by the commutator. In a simple machine of this type the brushes are shifted in one direction from the neutral if commutation is to be effected. This shifting of the brushes also supplies the wattless power needed in the armature. Now Mr. Journeaux proposes to shift the brushes (advance the axis of commutation) but to shift them in the wrong direction for commutation to take place normally. Then in order to effect the commutation, a portion of the brush circuit (that tube which has been carrying current) is to be forcibly opened. The commutating emf, therefore, must originate in the tube or brush itself. The commutating time will have a finite length depending on the magnitude of this tube voltage, and the inductance of the phase, as well as the angle at which commutation is caused to begin. During this time, must not the stored magnetic energy of the phase be dissipated in the tube? And will not the transformer associated with such a rectifier be larger than if this means of voltage control were not used? Furthermore, can the phase angle of the fundamental of the current wave be advanced by any desired amount? If the improved power factor is being obtained at the expense of additional loss and size of apparatus, the advantage of the proposed means might be questioned. I would like to ask if any actual test results are available on this scheme?

Didier Journeaux: In his discussion of the present paper, P. W. Blye considers the rectifier from the standpoint of inductive coordination with telephone circuits affected by the rectifier voltage or current. The formulas given in the paper, however, all relate to the continuous voltage of the rectifier, and none to the direct current. Although grid control causes the harmonic a-c components of the continuous voltage to increase appreciably, this action does not generally result in an increase of corresponding magnitude in the harmonic a-c components of the direct current, because, in general, d-c circuits apt to cause telephone interference, such as traction circuits, are highly inductive and the harmonic current components are choked to an extent proportional to their frequency. In general, telephone interference caused by rectifiers result from inductive coupling between the communication line and the power line. The extent of the disturbance is then proportional not to the voltage TIF of the rectifier, but to the current TIF, which may be computed similarly to the voltage TIF by the following formula:

$$TIF = \frac{\sqrt{\sum \frac{1}{Z_n^2}\left(\frac{H_n}{E_{do}}\right)^2 W_n^2}}{I_d}$$

in which Z_n is the impedance of the rectifier load circuit for the harmonic of order n, or its reactance if the circuit resistance is negligible compared to it, and I_d is the rms load direct current.

Curves a and b, Fig. 3 of this discussion, give the current TIF to be expected from a 600-volt 3,600-kw rectifier, feeding a d-c circuit having an inductance of 1 mh, the rectifier being uncontrolled or controlled, as in the example chosen in the paper, p. 987. The current TIF is thus obtained under the conditions causing the voltage TIF to follow the curves illustrated in Fig. 16 of the paper, and it will be noted that the current TIF, and therefore also the interference in telephone lines, are increased by grid control to a much smaller extent than the voltage TIF. The curves of current TIF may also represent the TIF for other values of the d-c line reactance by changing the scale of ordinates.

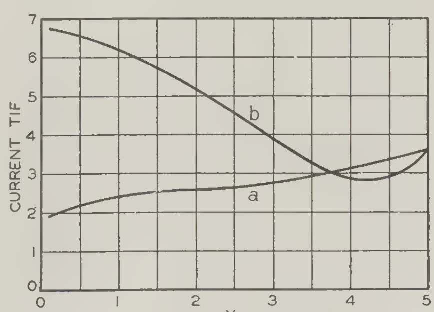


Fig. 3. Current TIF curves for a 600-volt, 3,600-kw rectifier

Grid control does not introduce any harmonics not present in unregulated rectifiers, for the reason that in either case the successive firing of the anodes causes the appearance of p identical ripples in the output voltage and current during each cycle, so that the frequencies of all harmonics must be the frequency, pf, of the ripple and its multiples in either case.

With regard to Mr. Herskind's discussion, the choice of the particular load factor in computations is largely a matter of convenience. For instance, in computations relating to 6-phase rectifiers with interphase transformers, coefficient K is equal to 0.01, and the working reactance is equal to the phase reactance multiplied by the ratio of the load value considered to full load, and may even be computed mentally, without reference to the actual values of the voltage and current.

In answer to the query of Mr. Stebbins I would state that the curves relating to interphase transformer operation, illustrated in Fig. 5, are based to some extent on oscillographic records of tests in which, of course, the assumptions of the paper could only be approximated.

Referring to C. W. Frick's discussion, the 12-phase connection referred to in the paper is the familiar connection considered on p. 152 of "Mercury Arc Power Rectifiers" by Marti and Winograd. The quantities I_p, E_p, and X_p, intervening in the computation of X_w, are the values of current, voltage, and reactance of the transformer, referred to the primary side.

The appearance of the 6th and 18th harmonics in the output of 12-phase rectifiers as a result of unequal division of load does not preclude the appearance of these and of other harmonics as a result of the presence of odd harmonics in the primary voltage. The effect of these primary harmonics, mentioned on p. 984, is general for all types of rectifiers.

The TIF curve illustrated in Fig. 16 was selected as being representative of the effects of flat regulation, and it was not desired to burden the figure with additional curves for arbitrary amounts of regulation at full

load, which would be without particular significance.

It is believed that the answers to the questions proposed by Mr. Ludwig will be found in reference 16 of the paper.

Although Mr. Hellmund's discussion does not directly relate to the subject of the present paper, it should be stated that the present paper was written much more as a synthesis of past performance than as a prophecy of what Mr. Hellmund calls "future possibilities of the pool-type rectifier." Out of more than 2,000 rectifiers of the general type illustrated in Fig. 2 of the paper, now in operation or under construction, and rated at a total of 1,700,000 kw, already more than 150 rectifiers, having a total output of more than 300,000 kw, are provided with grid control for voltage regulation or for current interruption. Of the above mentioned rectifiers 63 units, having a total output of 155,000 kw, are used for supplying d-c to electrolytic cells, showing that the application of rectifiers to electrochemical work is already an accomplished fact. The prospects of early application of the rectifier as a frequency changer certainly cannot be called unpromising, as 2 trial installations of frequency changers for supplying a-c railway lines are already being built or are in use in Europe (see *Elektrische Bahnen*, March 1932, p. 66, and *Elektrotechnische Zeitschrift*, Jan. 18, 1934, p. 65).

P. W. Blye: See discussion below.

Grid Controlled Rectifiers and Inverters

Discussion and author's closure of a paper by C. C. Herskind published in the June 1934 issue, p. 926–35, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

R. E. Hellmund: See p. 1396.

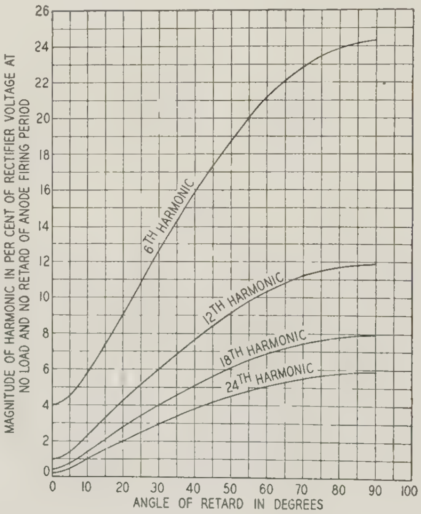
P. W. Blye: The papers by Messrs. Herskind and Journeaux are interesting from the standpoint of inductive coördination with telephone circuits because of the attention given to the effects of the grid controlled rectifiers on the wave-shape voltage and current of the associated a-c or d-c circuits. The effects on wave shape and the corresponding difficulties from noise interference on exposed telephone lines encountered with the usual type of rectifier is, I believe, well known. Information presented in these 2 papers indicates that the complexity of the problem may be increased by the addition of control grids.

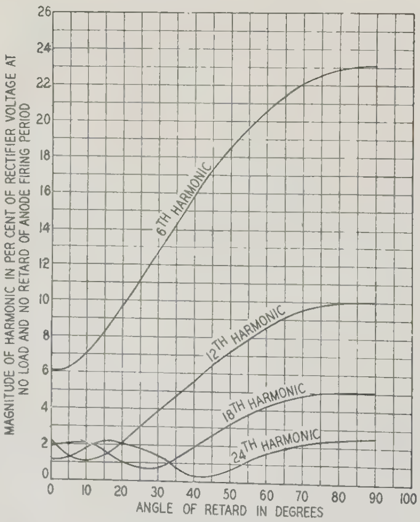
It is interesting to note that the addition of the control grids to rectifiers does not add any new harmonics to the system which would not be present without the grids. However, from the data given in the papers it seems evident that the magnitudes of the harmonics in both the a-c and d-c circuits may, under many conditions, be considerably increased. In order to reduce the wave-shape distortion to the same degree as without the control grids, more effective measures such as resonant shunts of lower effective resistance may need to be employed.

It is gratifying that recognition is being given to these wave-shape problems in the early stages of the development of these devices, so that orderly development of suitable measures for coördinating the power and telephone plants affected can proceed at the same time.

F. O. Stebbins: The author of this paper has presented a concise analysis of grid controlled rectifiers when the instantaneous d-c load current is constant. Since he does not give detailed information on the wave shape of the output voltage, a few outstanding points will be presented herewith.

Calculations and measurements on rectifiers without grid control which are now in service in the field indicate an angle of overlap of approximately 25 deg at full load upon the rectifier, though values over a range of from 12 to 30 deg were obtained. The use of grid control removes some of the limiting factors in rectifier design which influence the angle of overlap, but it will be assumed in order to simplify this discussion that these factors are still present.





Figs. 1 (top) and 2 (botton). Curves showing the 4 lower orders of harmonics for a 6-phase controlled rectifier: (1) at light load supplying a highly inductive d-c load; (2) at approximately full load supplying a highly inductive d-c load

Substituting zero angle of overlap in formulas 16 and 17 gives the magnitudes of the harmonics in the output voltage of a grid controlled rectifier at no load. The 4 lower orders of these harmonics as they appear in the output voltage of a 6-phase rectifier are shown in Fig. 1 of this discussion. Substituting 25 deg angle of overlap in formulas 16 and 17 gives the magnitudes of the harmonics in the output voltage of a grid controlled rectifier at approximately full load. The 4 lower orders of these harmonics as they appear in the output voltage of a 6-phase rectifier are shown in Fig. 2 of this discussion.

It will be noted from Figs. 1 and 2 that where a large angle of retard to give a wide range of voltage control is desired, the magnitudes of the harmonics in the output voltage becomes appreciable.

The output voltage wave shape of controlled voltage rectifiers has been analyzed for different conditions of loading in a paper by C. W. Frick and myself, which has been accepted by publication by the A.I.E.E. (Sept. 1934 issue, p. 1259–65.)

L. R. Ludwig: In discussing the duty on a grid-controlled rectifier, Mr. Herskind points out that in 2 ways this duty is more severe than in the case of the uncontrolled rectifier. First, the grid must block the anode when it is positive with respect to the cathode, and second, the anode must withstand a greater rate of rise of negative voltage at the end of its conducting period. It is interesting to note that in a controlled rectifier of the ignition type in which no grid is used the first of these added duties is practically nonexistent due to a complete absence of any arc or ionization in the vessel during the interval when the anode is positive.

In the portion of the paper dealing with the inverter the author has made reference to the "deionization time" (Fig. 11) which follows the conducting period. It would be very interesting to know the lower limits to the magnitude of this deionization time found during the tests with the experimental inverter.

It would be interesting to know also if the problem of pick up of the arc in the inverter has required modification of the excitation system from that used in the rectifier.

So far as the duty on the tubes is concerned, the inverter requirement has one advantage over the rectifier requirement when a counter emf load is being supplied. As shown by Mr. Herskind's Fig. 11, positive voltage is applied to the anode approximately as a sine wave of voltage with time, whereas in the rectifier circuit a considerable negative voltage is usually quite suddenly applied. A small negative voltage is also suddenly applied in the case of the inverter, but the magnitude of this voltage may be limited. During tests with an experimental ignitron inverter, for example, it has been found that the magnitude of this negative voltage needs to be only a fraction of that applied in the case of the rectifier.

Mr. Herskind has pointed out that rectifier-inverter equipment does not function in the same way as a motor generator set in

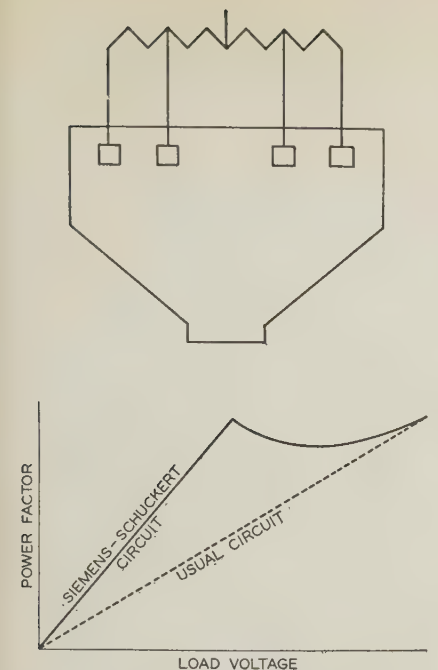


Fig. 3. Connections and variation of power factor with voltage of the Siemens-Schuckert type of voltage control

railway substations during periods of regeneration. That is, inversion does not begin automatically, and a pilot machine or other means are required for control. This proposed solution appears to be quite operative, and it forms the subject of U.S. patent 193,798 issued in Jan. 1933 to R. E. Hellmund and L. R. Ludwig.

The type of voltage control developed by Siemens-Schuckert has the advantage over the simple means of grid control which are shown of permitting good power factor over a wide voltage range. Extra anodes are required. The method has been described in *Siemens Zeitschrift*, Band 13, Sonderheft, p. 291, Oct. 1933. Figure 3 is reproduced here to show the connection used and the power factor variation with voltage.

As the rectifiers are improved and costs reduced, this method will show increased advantage over comparable schemes, such as transformer tap changing.

C. C. Herskind: In his discussion of this paper Mr. Ludwig has called attention to the fact that there are 2 types of controlled rectifiers: namely, the grid type and the ignition type. It is interesting to note that the same characteristics may be obtained from both, either rectifying or inverting, although the duty on the 2 is different, as Mr. Ludwig points out.

The deionization time required by the experimental inverter mentioned in the paper has a value estimated as less than 250 microseconds. In this connection it should be noted that when the inverter is operating near its commutation limit a large increase in the time available for deionization may be obtained by advancing the grid excitation only a small amount. This may be seen by reference to the curves on Fig. 9.

In order to assure pick up of the arc when operating as an inverter, it has been found necessary to provide the rectifier tank with more excitation anodes than is usual for rectifier operation. The experimental inverter was fitted with half as many excitation anodes as there were main anodes. One excitation anode was located between each pair of main anodes. All of the various schemes which have been devised for improving the power factor of controlled rectifiers operating over a wide voltage range involve costly complications. However, as the development of rectifiers is continued, these difficulties will undoubtedly be overcome.

Mr. Hellmund has reviewed some of the economic considerations involved in the various applications which have been proposed for controlled rectifiers. He has indicated the large number of possible applications. While the use of the rectifier is not now economically justified in many of these cases, we are confident that it will continue to develop rapidly as the technical problems are solved.

Factors Influencing the

Insulation Coördination of Transformers—II

Discussion and authors' closure of a paper by P. L. Bellaschi and F. J. Vogel published in the June 1934 issue, p. 870–6, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

L. V. Bewley: The scheme shown in Fig. 7 of the paper has been proposed during the last few years for the direct stroke protection of stations on both low and high voltage circuits. Various estimates and recommendations have been given for the length of the ground wire. In this discussion I wish to show how this length may be rationally determined; and in particular to point out that the length of the ground wire may have to be as much as several miles if the station capacitance is small.

Assume that the wave chopped by the line gap flashover is triangular in shape, rising to E kv in T µsec. As this wave travels along the line it suffers attentuation and distortion, but the total charge carried by it remains substantially constant. Examination of the oscillograms of chopped waves taken at different distances from their origin discloses that for the first mile or 2 the time to crest remains nearly constant, but the crest is rounded off and a tail develops, so that the wave acquires the typical shape of an impulse. However, when an attempt is made to represent this wave in the usual way as the difference of 2 exponentials, subject to the conditions that its average value shall be equal to the average value of the original triangular wave (that is, having equal charges) and that fronts shall be of the same length, it is found that the assumed wave shape is incompatible with the imposed conditions. Another possibility is to assume the wave shape of the form

$$e = AT\epsilon^{-at}$$

but in this case there are not enough parameters to meet the 3 conditions of amplitude, average value, and time to crest. A loop of a damped sinusoid also proves incompatible. About the only thing left which will permit analytic solution is to consider the arriving wave as still triangular in shape, rising to a voltage e_1 in time T, then falling to zero by time T', and with average value

$$\frac{1}{2}(e_1T') = \frac{1}{2}(ET) \quad \text{or } T' = \frac{E}{e_1}T \qquad (1)$$

The amplitude e_1 can be estimated by means of the Foust and Menger empirical attenuation formula,

$$e_1 = \frac{E}{1 + KEx} \qquad (2)$$

where

E = crest of original triangular wave
e_1 = crest of arriving wave
x = miles of travel = length of ground wire
K = empirical constant
$\cong$ 0.0006 for short chopped wave

The arriving wave is therefore

$$e = \begin{cases} \dfrac{e_1}{T}t & \text{for } 0 \leqq t \leqq T \\ \dfrac{e_1}{(T-T')}(t-T') & \text{for } T \leqq t \leqq T' \end{cases} \qquad (3)$$

When this wave strikes the station capacitance it produces a voltage at the station of

$$e_0 = \frac{2e_1}{\alpha T}[\alpha t + \epsilon^{-\alpha t} - 1] \text{ for } 0 \leqq t \leqq T$$

$$e_0 = \frac{2e_1}{\alpha T}[\alpha T + \epsilon^{-\alpha t} - \epsilon^{-\alpha(t-T)}] - \frac{2e_1}{\alpha(T'-T)}[\alpha(t-T) + \epsilon^{-\alpha(t-T)} - 1] \qquad (4)$$

where $\alpha = 1/ZC$, Z = line surge impedance, for $T \leqq t \leqq T'$ and C = station capacitance. Thus the station voltage can be computed directly in terms of the original wave and the length of the ground wire. As an example take

E = 1,600 kv	K = 0.000625
C = 0.001 µf	T = 0.4 µsec
x = 1 mile	Z = 500 ohms

Then by eq 2

$$e_1 = \frac{1{,}600}{1 + 0.000625 \times 1{,}600 \times 1} = 800 \text{ kv}$$

and by eq 1

$$T' = \frac{1{,}600}{800}(0.4) = 0.8 \ \mu\text{sec}$$

and by eq 4

$$e_0 = 2{,}000\,[2t + \epsilon^{-2t} - 1] \text{ for } 0 \leqq t \leqq 0.4$$

$$e_0 = 2{,}000[2.6 - 2t - 3.45\,\epsilon^{-2t}] \text{ for } 0.4 \leqq t \leqq 0.8$$

The results are shown in Fig. 1 of this discussion. The station voltage reaches a maximum of 720 kv. If the permissible voltage at the station is 530 kv, then by trial the appropriate length of ground wire is found to be 2 miles.

If the station capacitance is negligible, then the arriving wave doubles by reflection and

$$e_0 = 2e_1 = \frac{2E}{1 + KEx}$$

from which there is

$$x = \frac{2E/e_0 - 1}{KE} \qquad (5)$$

Thus if E = 1,600 and e_0 = 530, then

$$x = \frac{2 \times 1{,}600 \times 530 - 1}{0.000625 \times 1{,}600} = 5 \text{ miles}$$

It is therefore seen that a very moderate

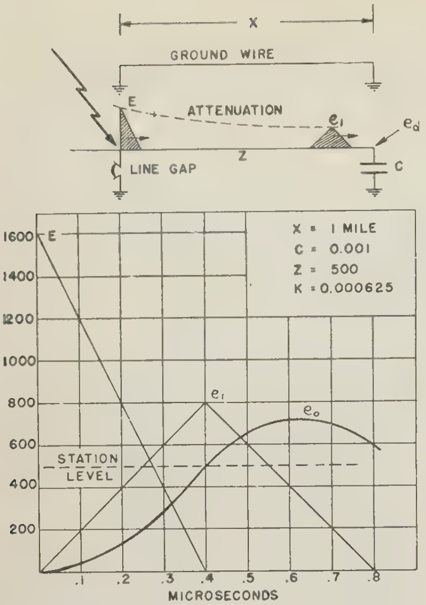


Fig. 1. Computation of station voltage

amount of station capacitance is quite effective in reducing the necessary length of ground wire.

The above argument applies specifically to circuits not equipped with reliable lightning arresters. For circuits so equipped the length of ground wire (on a most conservative basis) need not be longer than half of the length of the chopped wave. This means that in practice there is no real need for extending the ground wire for more than a normal span away from the station, if lightning arresters are provided.

J. E. Clem: The paper by Messrs. Vogel and Bellaschi touches briefly upon the problem of the protection of transformers. It seems reasonable that good operating engineering necessitates protective measures to keep service stresses at a reasonable margin below the strength of the transformer as demonstrated by the factory impulse test. This discussion will be supplementary rather than critical and will review briefly the problem of protection and the factors that should be considered in deciding how much protection should be provided.

In order to protect transformers it is necessary to know 3 things: the strength of the transformer, the probable overvoltages, and the performance of protective devices.

The A.I.E.E. proposed impulse test code applying to power transformers having voltage ratings of 15 kv or higher, which has been in use for more than a year, enables operating companies to purchase power transformers having an impulse strength subject to demonstration by test. At present the impulse test code requires that the transformer be tested in parallel with a plain rod gap, called the test gap, and the test demonstrates that the strength of the transformer is greater than that of the gap used. The strength of the transformer is determined on the basis of a positive 1.5×40-μsec wave and affords the operating engineers a definite basis on which to consider the need and value of protective measures.

Switching surges may range in magnitude up to $5^1/_2$ times normal voltage. These switching surges are usually of relatively long duration so that 60-cycle flashover characteristics of insulation usually must be considered in dealing with them. During the lightning investigations of recent years some evidence was obtained which indicates that switching surges in excess of about 4 times normal may have an appreciable impulse ratio.

Modern systems with directly grounded neutral are not affected by arcing ground troubles. Arcing ground overvoltages on ungrounded systems are of such duration that the 60-cycle flashover characteristics of insulation must be considered in dealing with them.

The problem of transformer protection can be simplified by considering the lightning overvoltages as divided into 3 general classes: direct strokes at the station; closely adjacent to the station; and more remote from the station, including induced strokes with the latter.

Direct strokes on the station structure will impose a very rapidly rising voltage, the magnitude of which will be limited only by the flashover of some piece of station equipment. As a rule the flashover voltage will be extremely high under these conditions so that extremely high overvoltages of relatively short duration will be imposed on station equipment.

Direct strokes on the circuits nearby will impose on the station insulation a very rapidly rising voltage of a magnitude dependent upon the flashover of the line insulation at the point where the stroke occurred. If the grounding resistance at the point in the line where the flashover occurs is high, a voltage dependent upon the current in the stroke will be built up and passed into the station. As a rule the rate of voltage rise at the station for these strokes is less than that for direct strokes at the station but the duration of appreciable overvoltages (caused by high grounding resistance) will be longer.

Direct strokes to the line at more remote points cause overvoltages at the station with a more sloping front and a lower magnitude than either of the 2 preceding. Induced strokes may impose on the station overvoltages of relatively slow front and of a magnitude limited in some cases by the flashover on the line insulation.

Since the overvoltages from switching and arcing grounds are usually considered on the basis of 60 cycles, it seems desirable to bring out the fact that the present accepted insulation levels are such that the problem of coördination as regards 60-cycle flashover characteristics is relatively unimportant. This is so because the 60-cycle strengths of the various component parts of the system are invariably above the overvoltages caused by switching and arcing grounds, so that there is usually no need to attempt to bring the 60-cycle strength of any part up to that of any other part.

Based upon the lightning overvoltages which might be expected, it is clear that it is necessary to protect transformers from both direct strokes and travelling waves. There are 3 types of protective equipment which may be used for this purpose: direct stroke shielding, lightning arresters, and plain air gaps.

Direct stroke shielding may take the form of ground wires over the station, of the steel structure extending above the circuit conductors, or of vertical projections extending above the plane of the conductors. Direct stroke shielding on the line usually takes the form of 1 or 2 ground wires above the conductor. To be effective the grounding resistance must be sufficiently low so that the *IR* drop will not build up sufficient voltage to cause a flashover between the direct stroke shielding and the circuit. An essential part of direct stroke shielding for a station is adequate shielding of the line out a sufficient distance to interpose surge impedance of the line between the lightning stroke and the apparatus to be protected. Briefly, adequate direct stroke protection requires that the lightning stroke be intercepted and discharged to earth without involving the equipment being protected.

In a case of direct stroke, extremely high values of current are involved so that lightning arresters cannot be considered as direct stroke protection because of the possibility that the lightning current may be beyond their capacity.

Lightning arresters may be used to provide protection from strokes on the line beyond the area of direct stroke protection. Modern arresters are available to meet certain specified volt-ampere characteristics which may be demonstrated by commercial impulse tests. The performance of these arresters is predictable, and this gives the operating engineers a definite basis for estimating the service stresses to which the transformers may be subjected when protected by them.

During the past few years in the study of coördination the plain air gap was given a status as a protective device which it did not merit. Plain air gaps will limit, by a flashover, the magnitude of the voltage applied to station apparatus and may be considered as giving a minimum amount of protection. The plain gap alone cannot be considered as a practical protective device for 3 reasons:

1. The volt-time characteristic of the gap is such that a higher and higher voltage is required to cause flashover as the time to flashover becomes shorter and shorter. Consequently, extremely steep wave fronts result in extremely high overvoltages before the gap flashes over. This imposes excessive overvoltages on the insulation being protected. In order to keep the stresses below the strength of the transformer, as demonstrated by the impulse test, it is necessary to keep the setting of the gap extremely low when the time to flashover becomes less than 2 or 3 μsec.
2. Flashover of the gap will usually cause a system outage.
3. If the setting of the gap is low enough to give a reasonable factor of safety below the demonstrated strength of the transformer, the gap may flashover on switching surges.

It is obvious that all stations do not merit the same treatment, and, consequently, there will be 2 varieties of protective set-ups. Large and important stations will be given complete protection, while the smaller ones may or may not be given partial protection.

Complete protection consists in adequate direct stroke shielding combined with the use of an arrester. With this arrangement the use of the plain air gap is not necessary for protection, and whether or not one is installed will depend upon the value given to the possible benefits resulting from it. The gap might be considered as a reserve in the contingency of the other protective equipment becoming inoperative, and also it might be considered as giving a check upon

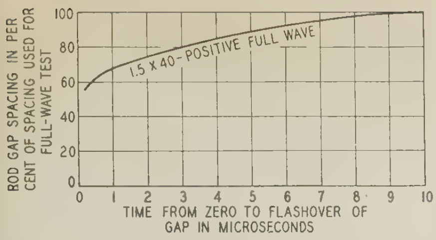


Fig. 2. Curve for estimating rod gap setting as percentage of test gap

the arrester operation. If the gap is installed it should have a setting not in excess of 90 per cent of that of the test gap used in the impulse test of the transformer at the factory. Briefly, complete protection consists in adequate direct stroke shielding and the use of a standard lightning arrester whose performance may be predicted.

Partial protection is provided by the use of arresters alone. For many years it has been common practice to use lightning arresters without direct stroke protection on 15-, 22-, 33-, and 44-kv systems. Modern arresters afford protection for such a station for strokes terminating on the line a moderate distance away so that the surge impedance of the line becomes effective in limiting the amount of current to be discharged by the arrester. All lightning strokes are not of the same magnitude, so that the arrester will discharge some of the milder direct strokes terminating very close or even at the station. For these stations the plain air gap can be used to limit the magnitude of the voltage for those cases where the lightning current is excessive.

If it is desired that the stresses in the transformer be kept below its strength as demonstrated by the factory impulse test, it will be necessary to reduce the setting of the plain air gap below the setting of the test gap. The amount of reduction will depend upon the assumed time to flashover. Figure 2 of this discussion may be used to estimate the setting. For instance, if it is desired to keep the same margin of safety for all flashovers occurring not sooner than 2 μsec to flashover, the setting of the plain air gap would be 75 per cent of that of the test gap. It should be recognized, however, that the lightning arrester may not be able to prevent the gap with a reduced setting from flashing over on long surges and, consequently, the setting of the gap must be a compromise between the protection desired and the possibility of an outage.

Where direct stroke protection is installed but the lightning arresters omitted, the station equipment may be stressed up to the flashover of the station insulation by lightning strokes terminating beyond the direct stroke protection, providing some means are not taken to limit the voltage. In such cases, the plain rod gap with reduced setting might be considered as an economic means of obtaining a minimum amount of protection. As before, the use of the plain air gap will necessitate a compromise between the amount of protection desired and the possibility of system outages.

When both the arresters and direct stroke protection are omitted some protection may be obtained at a minimum of cost by the use of a plain rod gap. As before, the setting of the plain air gap will be a compromise between the degree of protection desired and the possibility of outage.

There arise occasions when it is desired to consider the protection of transformers already installed. In such cases the procedure is to estimate the strength of the transformers in terms of the impulse test which could have been given when the transformers were built, and the procedure then is the same as outlined. It should be recognized, however, that the operation of the transformer without protection may have caused the insulation of the transformer to be damaged so that its present strength may be appreciably reduced, thus rendering the problem of protection more difficult or even impossible.

C. L. Fortescue: In this paper the principle of coördination has at last been presented in proper perspective. Following the intensive field investigation of lightning, there has been great activity in the various engineering laboratories in determining the impulse characteristics of various types of insulation structures. The determination of these characteristics for line insulation structures had progressed rapidly, outdistancing knowledge of impulse characteristics of insulation structures associated with apparatus such as transformers. Until this knowledge was available coördination was purely a matter of speculation, and as a result of this a stage of loose thinking has been experienced similar to that in transmission line insulation preceding the lightning field investigations.

As the authors show, 100 per cent coördination in the apparatus itself does not at the present time appear to be economically feasible, at least not with the use of edge gaps, because their impulse time lag characteristics do not correspond point to point with the true dielectric strength characteristic of insulating barriers. The sphere gap in this respect is the most satisfactory type of coördinating gap and it appears to be possible with a properly designed gap of this type to obtain 100 per cent coördination, but as the authors point out, it also has serious limitations. Prior to the field investigations, the theory of lightning arrester protection was on a rather unsubstantial basis, but this increased knowledge has brought about a better understanding of the requirements of arresters in the way of discharge capabilities. The further knowledge of the short time dielectric strength of insulating barriers brought about by this paper will, I believe, place the theory of lightning protection of apparatus on a secure basis.

What does the word coördination mean when applied to electrical apparatus? Does it not mean that the parts of the apparatus which are essential to its normal operation have a higher level of impulse strength so that if failure does take place it will be in some unessential part? The coördinating edge gap has been elected to be this unessential part, but as we see it has inherent defects for this purpose. First, its failure results in an interruption of service. Second, its impulse strength at time lags below 2 μsec is greater than that of the insulation with which it is associated. It is true that more insulation strength could be used with a given gap or for a given insulation strength a shorter gap could be specified, but this does not seem to be a satisfactory expedient. Unfortunately, the word coördination has been used by many during the past few years, as if in itself it had some mystic power, and in some quarters has been looked upon as a measure which would do away with the necessity of lightning arresters. But what is a lightning arrester but a coördinating gap with flat characteristics and having the additional ability of arresting the flow of power current after breakdown has taken place. Looked upon as a coördinative measure, the modern lightning arrester with its high discharge capacity appears to be closer to the ideal coördinating gap than anything that has yet been proposed, and as the result of the increased knowledge of lightning a continual improvement in their characteristics may be expected in the future.

In a paper by R. N. Conwell and the writer entitled "Lightning Discharges and Line Protective Measures," Electrical Engineering, July 1931, p. 478, the protective value of overhead ground wire for substations was pointed out. Prior to that date the Plymouth Meeting substation of the Philadelphia Electric Company and the Roseland substation of the Public Service Electric and Gas Corp. of New Jersey were protected with overhead ground wires, and subsequent to it, this type of protection has been installed over stations in practically every new high voltage development. It was pointed out in the paper that as long as the insulators supporting the conductors did not flash over when the ground wire was struck, the transformers in the substation connected to the line would be subjected to only a small potential as the result of a direct stroke to one of the structures. If corona on the overhead ground wires is ignored the actual potential impressed on the transformers would amount to the potential of the top of the structure receiving the stroke multiplied by the coupling factor between ground wires and conductors. Since this potential is not accompanied by any surge current there will be no building up of this potential at the terminals of the transformer; on the contrary the capacity of the transformer will pull down the potential. The energy of the resulting surge in the transformer winding will be derived from the ground wires through their mutual surge impedances with the conductors.

To form some idea of the magnitudes that might be expected, consider a 220-kv line entering a substation through a 1,000 ft span with ground wires 100 ft above ground level, and let us suppose the resistance of the structure footing to be 5 ohms at the station. The tower top potential per 1,000 kv of stroke potential will be about 137 kv. For a 20,000-kv stroke the tower top potential would be 2,740 kv reached in 1 μsec. If the coupling factor is 35 per cent the potential applied between the transformer terminals and ground will be 960 kv. If the tower footing resistance is so low that it may be considered zero the tower top potential will be 2,000 kv and the potential applied between transformer terminals and ground will be 700 kv. If flashover of the line insulators took place the line conductor would be raised to approximately the same potential as the ground wire after flashover had taken place, and this potential would be impressed on the transformer with all the energy in the tower top and ground wires

behind it. This potential is not the full potential of the tower top but what remains after flashover is completed and the conductor is charged; thus, for example, if flashover takes place after 2 μsec, what remains of the tower top potential would be less than 1,000 kv in the first case and a very small value in the second case. In the meantime, the potential of the point to which the transformer is grounded has also been raised to practically a like amount so that the net value of the surge entering the transformer terminal will be very small. If the line insulation were such that flashover took place on the front of the wave, say in $^3/_4$ μsec, then the line wire would take approximately the same potential as the ground wires had at that instant and thereafter.

The above discussion indicates why overhead ground wires for substation protection are not as effective for the lower voltages as for the higher voltages. The lower voltage substations and lines cannot justify the amount of insulation required to make them completely proof against lightning outages. There are, however, mitigating circumstances which make the protection level of the substation higher than that of the line. First, the height of the structures can be made considerably less than that of the towers, thereby reducing the tower top potential. Second, the distances between structures can be reduced so that the length of the tail of the tower top potential is reduced and if the span length is below 400 ft a substantial reduction of the tower top potential is also effected. The time permitted in a discussion of this kind does not allow me to go into detailed computations of these potentials for different heights of structures and spacings but they can be computed by the method of reflections, examples of which are given in my Paris paper, "Lightning and Its Effects on Transmission Lines," and the series of articles by Torok and Ellis, Monteith, and Beck which appeared in the latter part of 1933 and the early part of 1934 in the *Electric Journal*, reprints of which are available. It suffices to say that the effectiveness of ground wire protection against direct strokes depends upon the same factors as that of the transmission line itself and may be summed up as follows:

1. 100% shielding.
2. Low structures.
3. Short spans.
4. Low structure footing resistances.

If a transmission line emanating from a generating station is designed for an outage factor n per 100 miles per year and the generating station and substation has the same protection level, the probability of a lightning stroke producing a dangerous potential at the terminals of the transformers will be less than 2 n/100 per year. This is based on the assumptions that the exposure of a substation is equivalent to 1 mile of line and that there are 2 lightning flashovers for every outage. Illustrating this by a numerical example, the 132-kv lines protected by 2 overhead ground wires in the Great Lakes district show an outage factor of 1.7 per 100 miles per year. The probability of an outage due to lightning at a substation having the same level of protection as the lines is less than 3.4 per 100 years or 0.034 per year. This, of course, is a mass figure; it would be of little consolation to the utility engineer whose substation should be the one that is hit. From this it will be seen that for a line which is practically lightning proof the probability of an outage at a particular substation is very small.

In the case of an unprotected substation, the transformer is subjected to the full steepness of the lightning surge after it hits the line and until flashover takes place, then the potential is determined by the surge impedance of the tower and its footing resistance. With wood pole lines the potential to which the line may rise before breakdown is completed may be as high as 10,000 kv if the combined resistance of the pole butts to ground is of the order of 100 ohms. The danger to apparatus is higher the higher the insulation and with wood pole construction where there are no guyed poles in the vicinity it reaches its maximum. The probability of a dangerous potential from a stroke at a substation with wood pole construction is also high. If we assume that all strokes above 4,000 kv are dangerous the probability of strokes of this magnitude or larger causing dangerous potentials is for an isoceraunic (lines of equal thunderstorm occurrence) level of 30 approximately 0.24 per year, and for an isoceraunic level of 60 it will be double this or 0.48 per year.

G. D. Floyd: The authors state in the second paragraph of their paper that time lag curves still indicate that coördination is obtained even for surges of very short duration. As this point has been a subject of some controversy, I believe they might well have submitted the data on which their conclusion was based.

Previous papers on this and related subjects have been chiefly concerned with the strength of insulation and gaps against impulse voltages, and have given very little information as to how such data could be applied in practice. The authors of this paper have attempted to outline how such a problem should be attacked. It is to be hoped that as a result of the information now made available on the insulation strength of apparatus against surge voltages, the application of these data in station design will receive some attention, which should provide material for a very valuable paper.

I believe the question of service outages due to flashover of the coördinating gap has been stressed more than its importance warrants. If the station is a large one with several banks of transformers, each bank with its coördinating gap, the gap flashover will usually cause an interruption to service only if all gaps in the station operate. This is hardly likely to occur unless the surge is a very severe one indeed, in which case, if the gaps have adequately protected the transformers by having relatively low setting, the momentary interruption is nothing compared to the difficulty arising from loss of one or more transformers. If only one gap operates, the transformer bank and bus section associated with it will relay out, but the remaining transformer banks can usually carry whatever overload there may be until the transformer bank affected is picked up again.

If the station is small with a single circuit and transformer bank, it usually is of very little consequence if it be momentarily out of service. It is infinitely more desirable that such a momentary outage occur, if as a consequence the transformers are not damaged permanently. I believe that better all around results would be obtained if the coördinating gaps were set, say, 10 per cent lower than the equivalent gap corresponding to the voltage class of the transformer protected by the gap. This would provide an additional factor of safety, and would help to take care of possible deterioration in the transformer insulation due to the effect of repeated surges or to other causes.

K. B. McEachron: It is well recognized today that transformers should not be subjected to direct strokes, and that lightning arresters cannot be expected to perform all of their intended functions if the current associated with direct strokes is allowed to pass through the arrester. Therefore, for some time past, shielding of the station or substation, and adjacent lines and conductors, has been regarded as proper where economics allow the use of such protective means. To make such shielding effective, proper precautions with regard to ground resistance of tower footings and location of ground wires must be taken. The shielding need not extend more than $^1/_2$ mile from the station for this purpose.

The modern lightning arrester has characteristics which may be demonstrated by laboratory test; likewise the strength of the transformer can be demonstrated with reference to the assigned test gap. Thus it becomes possible to determine the margin between the arrester protection level and the transformer test gap with a reasonable degree of accuracy.

Frequently it is not economic to provide line shielding from direct strokes, and this is particularly true of the low voltage circuits where wood pole lines are used and no definite limitation of an incoming traveling wave provided, as would be the case with lines on steel towers. For such lines, expulsion protective gaps may be used on several poles adjacent to the station, thus limiting the traveling wave potential to values of the order of from 6 to 8 times normal line to ground crest potential. Of course, good grounds must be provided for the expulsion gaps, and as an added precaution the last gap or 2 could be tied in with the station ground using a buried conductor. Of course the expulsion gap on the line does not protect the transformer in the station, but could reasonably be expected to prevent direct stroke currents from reaching the arrester in the station unless the direct stroke occurred in the span adjacent to the station. Even in this event the gap would be helpful, as it would limit the length of tail of the impulse reaching the arrester.

Such use of the expulsion protective gap will have an additional advantage when used with arresters in the station, since limiting the potential of the incoming traveling wave will lower the protection level of the arrester and thus increase the margin of protection. If a reasonably definite level of line insulation through the use of the expulsion protective gap or other means is established, a greater dependence can be placed upon the arrester's performance than is now the case when there is no limit placed on line insulation except the wood pole itself.

Worth while reductions in arrester protection levels may be obtained at stations whose lines enter on steel towers if the insulation level is of the order of 10 times normal or more. In such a case, expulsion gaps located on the last few towers would bring the level of the incoming impulse down to the order of 6 to 8 times normal.

In those cases where ground wires do not perfectly shield the line from direct strokes, expulsion gaps would perform the same function as with the wood pole line.

It has been suggested that the lightning arrester be made the basis of coördination. This requires an arrester whose potential could be depended upon to maintain a certain margin below the transformer test gap for all kinds of lightning conditions in service. To do this requires some control over the impulses which reach the arrester, which means some limitation of the incoming traveling wave.

If the station and associated overhead lines are protected from direct strokes and a modern arrester installed in the station, there seems to be no good reason for installing gaps in the station, unless it be for the purpose of supplying a degree of protection in the event that the arrester is out of service.

If arresters are not used, the station gap to be effective for direct stroke conditions requires either an extremely low setting or else shielding of the line over a considerable distance, as indicated in Mr. Bewley's discussion.

H. V. Putman: When the transformer subcommittee undertook the formulation of recommendations for impulse testing 2 years ago, one of the principal points of discussion centered around the possibility of damage to the insulation during test. The subcommittee recognized this problem but considered that it was reasonably safe to proceed with impulse testing because it did not appear that the problem of insulation damage in connection with impulse tests was much different than the problem of insulation damage in connection with the regular low frequency dielectric tests.

In my talks with utility engineers I have occasionally run across an engineer who was unalterably opposed to impulse testing because of the possibility of damage to the insulation. The data presented in this paper I think will do much to settle this question and will allay the fears of those who have felt that impulse testing was dangerous. I believe it will therefore help to establish impulse testing on a firmer foundation.

The subcommittee now has before it certain proposals for simplifying impulse testing procedure and making it more effective. At the same time the manufacturers have occasionally received requests for very much more complicated and expensive impulse testing procedure consisting of a large number of tests at very steep wave fronts with the test gap flashing over on the rising front of the wave. These requests have come from engineers who have not been fully satisfied with the test procedure recommended by the subcommittee, and who have felt that these recommended tests were not an adequate demonstration of protection against very short waves.

It is obvious that the work of the committee is not successful unless its recommendations can be accepted by the industry, and the subcommittee is anxious to have its recommendations reflect the needs and desires of the industry. The test procedure recommended by the subcommittee has only one purpose and that is to demonstrate a given level of insulation in the transformer. It is not their purpose to demonstrate the effectiveness of any scheme of protection. The data presented in this paper enable one to determine what the performance of a transformer will be under a large number of repeated surges at very short time lags if one knows the insulation level which is demonstrated by the regular tests. Therefore, I hope this paper may help to avoid any need for a test procedure involving large numbers of impulses at very short time lags—tests which are often difficult and sometimes impractical to make, particularly on large transformers.

V. M. Montsinger: I believe that everyone will agree that this paper is a valuable contribution to the subject of coördination of transformers and also to the material given in the symposium of papers presented on the same subject at the winter convention in January 1933.

This paper is of particular interest to me because it presents the results of an investigation quite similar to one which I have been following; namely, to determine (1) the effect that various shapes of impulse waves have on the breakdown of transformer insulations, (2) the effect that repeated applications have on the breakdown of transformer insulations, and (3) a study of the best means of providing protection in the field against steep waves associated with direct strokes on or near the terminals of transformers.

I have noted with interest that the authors obtained practically the same average "impulse ratio" that was given in the paper "Coördination of Insulation" (V. M. Montsinger, W. L. Lloyd, Jr., and J. E. Clem) presented at the 1933 winter convention. As a matter of fact, it is a little higher for barrier B, being 800 kv for the single impulse failure divided by the 60-cycle 1-minute failure of 316 kv crest, or 2.53. Our data indicated a ratio of 2.35. At that time Mr. Vogel's data indicated a ratio of 2.2. The average of 2.2 given for barrier A and 2.53 for barrier B is 2.37; consequently, we now agree quite closely on the average impulse ratio of the major insulation of transformers.

The statement that the insulation and point gap characteristic curves are closest at 2 μsec is too important to pass over without comment. I take this statement to mean that the margin between the insulation and a rod gap, if tested in parallel, is a minimum at 2 μsec as indicated by the volt-time curves covering the entire range of waves, including the steepest fronts. In other words, if a gap just protects a transformer at 2 μsec time, there is no danger of it not protecting it at any other time of flashover either shorter or longer than 2 μsec. If my interpretation of their statement is correct (and I don't see how it can mean anything else), this statement is not consistent with the data given later in the paper where it is shown (1) that the full 1.5×40-μsec wave single-shot equivalent gap breakdown of barrier B is approximately 50 in. (800 kv), (2) that the 2.5 to 4 μsec repeated-shot equivalent gap breakdown is around 30 to 35 in. (610 kv), and (3) that the repeated short chopped wave equivalent gap is 14 in. (600 kv).

The data in Table III of the paper on "Coördination of Insulation" referred to above (later tests also bear this out) show that the equivalent rod gap spacing (to protect insulation) must be continually decreased as the waves become shorter and steeper. This is also shown in the volt-time curves, Fig. 2 of the same paper.

This data together with that cited for barrier B seems to prove beyond any reasonable doubt that the volt-time curves will cross if the insulation strength is above, but not too far above, the gap strength for long waves.

I would like to ask how many shots the dotted line in Fig. 1 entitled "several shots" represents? The word "several" is too indefinite to mean very much.

In reference to the data on barrier A which shows that the voltage values are approximately the same for full 1.5×40-μsec waves and waves chopped in 2.5 to 4 μsec, I would like to ask at what point on the waves failure took place in the insulation. In our work we find that puncture of solid insulation (or solid and oil in series) almost invariably takes place quite near the crest of the wave. It seems to be almost impossible to get it to break well down on the tail of the wave. This probably accounts for the authors obtaining approximately the same values on barrier A for both full waves and waves chopped beyond the crest by a rod gap within 2.5 to 4 μsec. We have found that the flashover of a full wave causing failure by creepage usually takes place well beyond the crest, the same as it does for the sparkover of an air gap.

I think the authors have handled the definition of short waves rather loosely. They call any wave that flashes over between 2.5 and 4 μsec a "very short wave." To me a "very short wave" means one that flashes over around 1 to 2 μsec. I should define them as either "moderately short waves" or "short waves." I agree with their definition of "extremely short waves" as waves which flash over in approximately $^1/_2$ μsec.

With reference to the effect of repeated shots on the breakdown of insulation, I would like to suggest that the "interval between shots" be given. This may be an important factor when making life tests.

Our tests in which failure is either by creepage or puncture show that to prevent markings and failure after a large number of shots the equivalent gap must be set at not over approximately 70 per cent of the single shot breakdown value.

As shown previously in Table III of our paper on "Coördination of Insulation," the equivalent gap spacing for extremely short waves may be as low as from 35 to 40 per cent of the full wave equivalent gap.

The data in the paper does not reveal what the equivalent gap for the life tests on barrier B with full waves was, but when applying the same percentages as cited above, we agree quite closely on the equivalent gaps for a single shot failure and failure for a large number of steep waves. For example, 70 per cent of the single shot equiva-

lent gap of 50 in. (800 kv, Fig. 1) gives a 35 in. equivalent gap for the life test strength as obtained with full waves. Now 40 per cent of the 35 in. gap gives a 14 in. gap for the equivalent gap for the life tests made with extremely short waves. Their values in Table III are 14, 14, 14, 14, 16, and 17 in.

I believe that there is one conclusion that is irrefutable; namely, that it is not possible from an economic standpoint to protect transformers from severe direct strokes of lightning simply by either increasing the insulation or by reducing the line insulation at or near the station. Something more must be done to keep the direct strokes off the nearby lines. Overhead ground wires and modern arresters supplemented by a rod gap whose spacing is as low as the arrester can protect, or not too low to give undue outages from switching surges, seem to be the answer in the present state of the art.

With reference to the present method of impulse testing of transformers, I believe that we have now progressed far enough to consider modifying the tests to fit in more nearly with the latest methods available for protecting transformers in service. I refer particularly to modern lightning arresters which have practically flat volt-time characteristics, quite similar to the volt-time curve of a sphere gap.

In view of the fact that we now have available protective equipment—the arrester—which holds the crest of the impulse voltage to practically a constant value, I propose that the Institute consider modifying the present method of impulse testing of commercial transformers.

In a general way the present method of testing would be supplemented by chopping off the 100 per cent impulse test gap wave on the crest by a sphere gap and then applying a sufficient overvoltage across the same sphere gap setting to cause flashover on the front of the wave.

In this manner the transformer would be tested with the entire range of impulse waves to which it can be subjected in service provided, of course, it is properly protected.

If it is decided that it is advisable to modify the method of impulse testing, the details should be worked out by the proper technical committee, either the transformer subcommittee of the electrical machinery committee or the A.S.A. sectional committee on transformers.

P. L. Bellaschi and F. J. Vogel: All the discussions are in general accord that the problems of coördination and their solution, proposed in our paper, are fundamentally sound. Specific questions have, however, been raised and certain viewpoints expressed which warrant reply.

There has been some misunderstanding of the data presented in Fig. 1 of the paper, so it may be well to explain in greater detail than stated in the paper the various curves given in the figure. The full line under "barrier" represents failure for single surges of the duration indicated. This barrier was similar to barrier *B* described in the paper. We note a rapid increase in strength with decrease in the length of the surge below 2 μsec. These data confirm the conclusion No. 1 reached in the paper that "Transformer insulation of conventional types is probably coördinated with the proposed standard coördinating gaps, except that, in the case of very high short surges, marked deterioration results." The dotted curve shows the results obtained in the previous paper. In this case the applied voltage is gradually increased from approximately 10 per cent below breakdown up to failure. Successive surges of increasing magnitude were therefore applied in the procedure of these tests. Several surges, as described in the paper, should therefore be construed to mean these surges taken in increasing intervals, which were in the order of 6 to 10 in number.

Obviously, from the impulse voltage value of the dotted line, 730 kv, and the 1 minute hold 60-cycle crest for this barrier of 316 kv, the impulse ratio is close to 2.2. This ratio was fully established in the preceding paper.

It is therefore seen that the data are actually furnished in the paper upon which the statement is based that time lag curves still indicate that coördination is obtained even for surges of very short duration. This question was raised by G. D. Floyd. Coördination here is, however, interpreted to mean that the impulse strength of the transformer under single surges should be stronger than the impulse strength of the gap even for surges of very short duration. Figure 1 in the paper actually shows these relations between a coördinating gap and the major insulation in a transformer, and is generally representative.

Mr. Montsinger has commented upon the statement that the insulation and point gap characteristic curves are closest at 2 μsec. A further detailed discussion of what is meant by this statement therefore appears in order. What was meant was that the insulation and point gap characteristic curves were closest at approximately 2 μsec if single surges only were to be applied, which is obvious from Fig. 1. However, nothing is said as to the effect of deterioration or what would have happened to this barrier if repeated surges of the same magnitude had been applied. If repeated surges are applied, it is readily seen from the dotted curve and the gap curve that the 2 curves intersect at some definite short time lag depending upon the insulation and gap levels.

As Mr. Montsinger has found out, we also have found that puncture of solid insulation almost invariably takes place near the crest of the wave, whereas for creepage around barriers failures are characterized by distinct time lag curves much the same as for rod gaps. With respect to the time interval between shots for the tests with repeated impulses, the interval was varied over a wide practical range in our tests with apparently no effect whatever upon the results. We believe that this is reasonable when we consider that deterioration occurs at some definite voltage gradient. Being of a disruptive nature rather than due to the effects of heat, it should be independent of the time interval between voltage applications.

We agree with Mr. Montsinger's value of 70 per cent as the ratio between the equivalent gaps for a large number of shots in contrast to the single shot breakdown value in the case of puncture. This is not necessarily the case for creepage breakdowns.

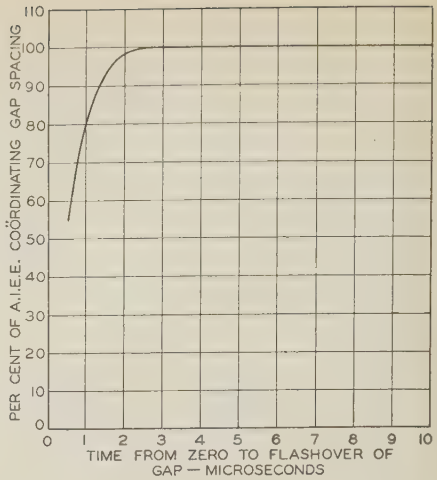


Fig. 3. Gap coördination for negative surges

Gap spacing expressed in per cent of standard A.I.E.E. edge gaps for constant factor of safety in power transformer insulation

We are interested in Mr. Clem's statements as to the impulse strength of transformers. He states in his discussion under the subtitle of "Strength of Transformers" that the strength of the transformer is demonstrated to be greater than that of the gap used. This statement appears to us to be inaccurate when thoroughly analyzed. In the beginning (A.I.E.E. TRANS., v. 51, 1932, p. 923) the edge gap was advocated as a means of coördination. In the previous paper (A.I.E.E. TRANS., v. 52, 1933, p. 411) on the same subject it was indicated that coördination of major insulation or of a surge proof transformer was generally obtained down to 2 μsec. Furthermore, in this paper it has been shown that major insulation or a surge proof transformer should stand surge voltages of a magnitude represented by the flashover of a coördinating gap near 2 μsec. This paper also gives complete data for edge gaps for time lags below 2 μsec and for very high rate of rise of voltages. In addition we must take into consideration the polarity of the surge. It has now been well established that the higher voltage surges in service are negative in polarity. Full waves with negative polarity may be a considerable percentage higher than positive waves and even at 2 μsec the flashover of edge gaps for negative waves is still somewhat higher than for positive. Therefore it seems time to take account of all of these facts and consider the subject of coördination with gaps upon a more logical basis. It seems then reasonable to base coördination upon negative surges as limited by the standard coördinating gap. As the 2-μsec value of the gap approaches the insulation level and therefore, as stated completely in the beginning of this discussion, this is the critical point for both 2 μsec and longer waves, it seems logical that the gap setting be based corresponding to this point, thus covering automatically and completely waves of greater duration. However, for shorter waves of durations as indicated in Fig. 5 of the paper, if deterioration is to be avoided a derating of the gap is essential. Taking into account all these facts, Fig. 3 in this discussion gives our recommended equivalent coördinating gap levels for wave duration from a

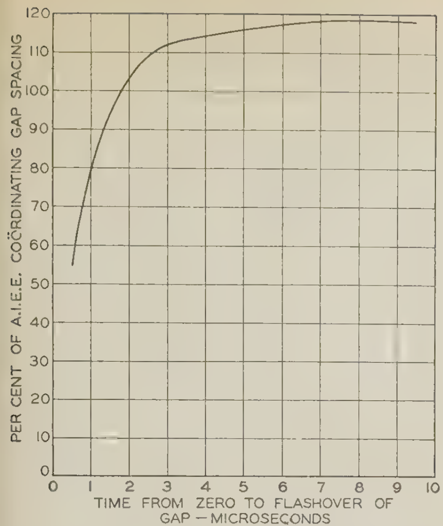


Fig. 4. Gap coördination for positive surges

Gap spacing expressed in per cent of standard A.I.E.E. edge gaps for constant factor of safety in power transformer insulation. This curve is based on the requirements for negative surge coördination

fraction of a microsecond through the critical 2 μsec and greater.

It will be noted from Fig. 1 that surge proof transformers are just as strong as the coördinating gap for negative surges. Also an inspection of the time lag curves for positive and negative waves will show that the present A.I.E.E. tests do not demonstrate this. For example, the test on a 230-kv transformer, according to the present test code, need be only 1,240 kv, whereas a surge of negative polarity chopped at 2 μsec with a 64 in. gap would impose 1,430 kv. It is for this reason that the authors have advocated a change in the test code to provide a test of at least 2.9 times the 60-cycle test voltage. An example of a test of this kind was reported in the paper for a 230-kv surge proof transformer. Mr. Clem has stated, as indicated by his Fig. 2, the policy of his associates in giving out the strength of transformers in terms of the impulse tests which could be applied. We prefer to give out the values which could be applied at 2 μsec, indicated in our Fig. 3. If this figure is translated in turn to correspond to gap lengths for positive surges, we obtain Fig. 4 which is merely of academic interest; however, it may be useful for comparing with other data.

Modifications to the present transformer test code have been proposed but we see no reason for making any change in the test code other than to increase and conform its severity in line with service requirements, as indicated by the coördination problem, and to provide a further simplification in the test code.

A considerable part of the discussions by Mr. Bewley, Mr. Clem, Mr. McEachron, and Dr. Fortescue pertain largely to the problem of protection against direct strokes. In substance, these discussions are well covered in our paper under "The Coördination Problems: Direct Strokes and Short Waves," and in fact we see nothing really new except possibly a detailed extension of the basic principles we have developed. The general use of the ground wire over stations is now well known and it has been used for a number of years, as outlined in Dr. Fortescue's discussion. However, we believe that the use of 2 gaps or protective devices, as indicated in Figs. 7 and 9 of the paper, were first proposed by the authors, as described in the A.I.E.E. Trans., June 1933, p. 445. Furthermore, the present paper covers the effect of repeated surges on insulation and its deterioration. All these important additional facts underlying the protection problem against strokes, and their proper coördination, are developed in the paper into the methods of protection indicated in Figs. 7 and 9 of the paper. These methods of protection in the final form indicated are, we believe, original contributions of this paper.

We are in accord with the analysis of Mr. Bewley on the shielding and protection of substations against direct strokes. In considering chopped waves traveling over a considerable distance, such as 1 mile as is considered by Mr. Bewley, the authors have clearly stated that account must be taken of attenuation. The analysis Mr. Bewley presents is a specific application of the fundamental principles developed in the paper; in fact the eqs 4 which he gives may readily be arrived at from the application of eq 1 in the paper. However, even in the case he considers, multiple coördinating gaps will serve a useful purpose.

Both Mr. Clem and Mr. McEachron have given a very complete and detailed discussion of protection against surges and direct strokes. The general facts, stated in their discussions, are well recognized and accepted.

In the paper an important statement was made that the question of transformer protection against direct strokes was one of economics in that it might be decided to run the risk of failure due to direct strokes, or to so coördinate the transformer insulation that it would withstand direct strokes, or to avoid any possibility of direct strokes at the apparatus. Of these 3 propositions it appears that the second proposition is not feasible. This appears to be generally agreed to. The third proposition is the most expensive since it involves shielding by means of ground wires, gaps, lightning arresters, and ground networks, but such applications may be fully warranted in large and important stations. In such stations not only freedom from outage but no possibility of deterioration of the apparatus within the station can be permitted. From the requirements of such a station to those of smaller and generally less important stations the degree of risk which may be run may extend over a considerable range. Consequently, with smaller and less important stations various protection schemes are possible, each adapted to the economics and the risks of the particular station in question. The greatest amount of risk may obviously be run in small stations where an occasional outage or some deterioration or transformer failure may be well compensated in reduced cost of substation expense.

It might be of interest here to furnish an idea of the degree of risk which might be encountered in a station using the least amount of protective equipment, such as the coördinating gap alone. In conjunction with the smaller and less important stations, which are no doubt numerous, an idea of the amount of risk incurred is illustrated in the very interesting discussion given by Dr. Fortescue. Referring to his example on 132 kv lines having ground wire protection, the probability of an outage due to lightning near and at the substation is once in 30 years. In such a case it seems reasonable to expect good performance from a plain rod gap coördination. However, where lightning is more severe and in general for constructions involving wood pole lines, as indicated by both Dr. Fortescue and Mr. McEachron, additional protection in the way of a lightning arrester seems desirable. In actual practice this is particularly the case for low voltage lines ranging from 15 kv to 44 kv. These observations are to some extent justified by the fact that transformers in the past, which were obviously very poorly protected, still have had a remarkably low mortality. On the other hand, exceptions have been brought to light where transformers in certain localities have had repeated failures. These conflicting data show the probability of obtaining fairly good protection for transformers in stations of small and no importance and equally well the desirability of providing all the protection for stations that are large or of great importance. To this general statement we may add that occasionally in small stations, where lightning severity is unusually high, either for geographical or topographical reasons, better protection than is normally used for such a station is justified.

Insulation Resistance of Armature Windings

Discussion of a paper by R. W. Wieseman published in the June 1934 issue, p. 1010–21, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

P. L. Alger: I should like to emphasize the fact that Mr. Wieseman's paper is not intended to set any definite standard or allowable limit of insulation resistance for any purpose. The paper is chiefly intended to explain the known types of variation which occur in insulation resistance, particularly the effects of dimensions and other design characteristics.

By suggesting a definite test procedure, pointing out the importance of moisture and temperature effects, and giving the definite effects of design changes, it is intended to bring out in clear relief the remaining factors of variation. Study of these remaining factors should enable much valuable information on insulation condition and life expectancy to be obtained.

I am convinced that, despite the tremendous and seemingly erratic variations in insulation resistance which are known to occur, patient analysis will finally disclose the reasons for, and thence the meanings of, all these variations. Hence, I believe that we shall in time be able to tell a great deal about the fundamental quality, the present condition, and the likelihood of failure of insulation of machines under operating conditions, if we pursue the study which Mr. Wieseman has thus well begun.

I should like to appeal particularly to the

operating engineers to obtain data by the methods Mr. Wieseman suggests, or other methods which may be found expedient, and to publish their data so that a rational technique can be developed for judging machine insulation in the manner already laid down in the testing of cable and bushing insulation.

The present situation in regard to insulation appears to me much the same as that of core loss 30 years ago. It was then repeatedly said that core loss could not be predicted and was too erratic to make it worth while to attempt its calculation. Nevertheless we can now predict the core losses of most machines to within a very few per cent, and the studies that led to this result also led to very important improvements in design. Similarly, by studying insulation resistance we should find not only better means for judging insulation but also means for improving it.

K. A. Reed: I regret that the discussion of this paper was closed before all discussers had an opportunity to present their views. inasmuch as oral discussion at the time of the presentation of a paper is much more effective than written discussion that is published at a later date.

The author is to be commended for his contribution to a subject to which we have devoted much study over a long period of years, but one to which some of our electrical manufacturers have given scant consideration until within the past few years. We hope that the subject will continue to receive due attention; at least until such time as better and more definite means are devised for obtaining information concerning the condition of the insulation of electrical apparatus.

We agree with Mr. Wieseman that the minimum insulation resistance formula embodied in the A.I.E.E. Standards for many years is of no real value, since the results obtained from this formula are, by far, too low for the safe operation of electrical apparatus. We have endeavored for a long time to bring about a proper change in the formula, and the subject was discussed with the National Electrical Manufacturers' Association early in 1927 in an effort to obtain some action from that source. A revision of this formula has been under consideration by the electrical machinery committee of the A.I.E.E. for the past 2 or 3 years, and the formula it has recommended for adoption is inadequate.

A number of points brought out in Mr. Wieseman's paper will be discussed in the order in which they appear. With respect to item No. 1 at the beginning of the paper, many cases arise where a single insulation resistance reading taken under the conditions mentioned does have a great deal of significance. For example, a machine may be removed from service and a reading taken while the machine is hot shows the insulation resistance to be low, despite the fact that the machine appears to be clean and there has been no opportunity for the winding to absorb moisture. There may be a coil loose in its slot and the chafing has worn the insulation to a dangerous point, or the low reading may be due to numerous causes. The discovery of such a condition by taking a random reading may avoid the breakdown of a winding.

With reference to the latter part of item 3, it is practically impossible to determine in the field, without cutting into the insulation, whether class A or class B insulation has been used, and formulas that take such items into account are impracticable for field use.

We disagree with the first part of item 11 which states that a low insulation resistance is the result of several months of moisture accumulation because the winding requires considerable time to absorb moisture. There are many things other than moisture that cause low insulation resistance and many cases come to our attention where, under certain "operating and local conditions," low insulation resistance may develop within a few days with respect to a winding that remains dry when the machine is in normal operation.

The items that are taken into account by the author in devising his formulas for armature winding insulation resistance, as shown on p. 1011, may be all right for exact values that are desirable in a laboratory, where storage batteries and other unusual test apparatus are available, but we do not believe that for ordinary practicable purposes so many variables are either necessary or desirable. It is, of course, true that the large, slow speed machine has a much greater area of insulation exposed to iron than a small machine or a high speed machine and, in general, one might expect to find the insulation resistance of the former machine lower than that of either of the 2 latter machines when all are subjected to the same operating conditions. However, from actual experience, we have found that such is not the case, as will be outlined later in this discussion.

Among the disadvantages that are involved in the author's scheme are:

1. Armatures only are covered.
2. Numerous formulas are required, one each for machines of several types and capacities.
3. Many variables are involved, such as the class of insulation on the winding, the relative humidity, whether or not the machine is clean and dry, built in the summer or the winter, etc.
4. A great many constants are involved and it appears that they are of a more or less arbitrary nature.
5. "Reasonable assumptions" are made and "average values" are used for certain factors that vary somewhat from one machine to another.
6. Special consideration has to be given a single-phase machine if it is equipped with a 3-phase, wye connected winding.

The author has very ingeniously devised a scheme whereby the numerical solving of more or less complicated equations is avoided, and this scheme would, doubtless, be of tremendous value to many maintenance men. However, a material amount of graphical computation is still necessary and it would be impracticable for a person to carry around with him a number of sheets applying to different types of machines from which he could determine the insulation resistance of various sizes and kinds of armatures, only to find it necessary to obtain the insulation resistance of the other parts of the machines in some other manner.

From our point of view, there is only one purpose for which insulation resistance is determined, namely, to obtain a "more or less" definite indication as to whether or not the condition of the insulation of a given machine is such that it is safe to place the machine in service. We are not at all interested in exact or specific insulation resistance values, but, on the contrary, we are extremely interested in a certain minimum insulation resistance value for a given machine that is based upon the voltage of the machine. This value is 1 megohm per 1,000 volts rating of the machine as shown on its nameplate, with a minimum of 1 megohm for machines that are rated at from 100 to 1,000 volts. Such a minimum value applies to the windings of all types of rotating machines, transformers, starting apparatus, etc.

During the past 12 years we have taken more than 750,000 insulation resistance readings throughout the United States and Canada. These readings have applied to all types and capacities of electrical apparatus, and they were taken with care by experienced engineers under all weather and load conditions that arise. Throughout this entire experience we have invariably found that when the windings of a piece of electrical apparatus are in proper operating condition, a minimum insulation resistance reading of at least 1 megohm per 1,000 volts rating of the object can always be obtained.

In view of the fact that minimum insulation resistance values such as those just described have been found by a very broad experience over a long period of years to indicate that windings with such insulation resistances are safe to operate, it appears to us to be unnecessary to spend considerable time in an effort to develop exact values that will, in a very large percentage of cases, be higher than the minimum necessary for safe operation. The method of procedure that we are following gives instant results and it is definitely known without any computation whether or not the object requires attention. It is, of course, essential to properly analyze insulation resistance readings with respect to weather conditions, whether the machine was hot or cold, etc., inasmuch as these factors may influence the value of the information that the readings are intended to develop.

We are in disagreement with that part of Mr. Wieseman's discussion of his paper at the time of presentation wherein he expressed the view that practically all insulation resistance readings are improperly taken. Our method of procedure is uniformly followed by all field engineers and the results obtained make it clear to us that we are "getting somewhere" along this line. I might further add that our experience has shown that the minimum values we have set up may always be obtained regardless of the capacity, type, or speed of the machine, and our readings are taken with conventional types of ohmmeters and meggers.

In the examples shown by the author in Figs. 9, 10, 11, 12, and 13, minimum insulation resistance values of 0.65 megohms, 2 megohms, 0.9 megohms, 0.6 megohms, and 0.6 megohms, respectively, are given for armatures only. We would expect to obtain on all windings and other insulated parts of these objects minimum insulation resistance values of 4 megohms, 2.5 megohms, 1 megohm, 1 megohm, and 1 megohm, respectively, and if such values were not obtained, insurance would be withheld until the causes of the low readings were located and removed and the insulation resistance values brought up to the minima prescribed.

S. L. Henderson and **J. F. Calvert:** This paper is of value for the many important points concerning the resistance of armature insulation which are carefully summarized at the first of this paper. Most of the facts emphasized here are well known, but when assembled in this concise form they should furnish a more solid foundation for the future discussion of insulation resistances.

A further contribution is the discussion of the relations between armature resistance and time. This indication of the condition of armature resistance may prove quite useful, particularly to operating engineers.

The fact that the formulas are complicated by fractional exponents has been very neatly overcome by the introduction of graphical methods of calculation which are very easy to use.

A comparison is given between the proposed American Standards Association method of calculating insulation resistance and the methods proposed in this paper. We believe that a comparison with actual test data is the important thing here and that it is very unfortunate that this comparison is not made. Test data is the only thing which can be used as the basis for judging the real merits of these formulas. We believe that if such data were taken on "run of mine" cases such variations would be found in the test data that the differences obtained by the different formulas would seem much less important. The fact that tremendous differences in test data may be expected is shown by the very large allowable variations in the equation constants given in Table I of Mr. Wieseman's paper. In one case a 12 to 1 range is allowed for good insulation, all at the same temperature. Of course, a very large variation is to be expected with temperature, for in many of the bonding materials used in built up mica insulation the resistance decreases many times as the bonds reach temperatures where they become fairly plastic.

In the past few years, considerable data have been collected on insulation resistances by another of the large manufacturing companies. The following is summarized from tests on over 300 machines:

I. Tests on Induction Motors at the Factory:

Number of machines tested—43
Insulation—class A
Temperature—"cold" or about 21 deg C
(All but 4 measured armature insulations were 100 megohms or above. These 4 were 14, 30, 30, and 50 megohms.)
Percentage of the machines failing to test up to the calculation values:
By Wieseman's formula using $K_i = 0.015$, the value given for good operation at 21 deg C........... 25.6 per cent
By the proposed A.S.A. formula $\dfrac{E}{\frac{\text{Rated kva}}{100} + 1{,}000}$ None
By the proposed A.S.A. formula times 40...................... 9.3 per cent*

II. Tests on Induction Motors at the Factory:

Number of machines tested—17
Insulation—class A
Temperature—"hot," or about 75 deg C
(The range of measured insulation resistances was from 4 to 100 megohms with approximately half of the machines having resistances of 45 to 100 megohms.)
Percentage of the machines failing to test up to the calculation values:
By Wieseman's formula using $K_i = 0.0002$, the minimum value given for 75 deg C.............. None
By the proposed A.S.A. formula $\dfrac{E}{\frac{\text{Rated Kva}}{100} + 1{,}000}$ 5.9 per cent
By the proposed A.S.A. formula times 4........................ 5.9 per cent

III. Tests on Turbine Generators at the Factory:

Number of machines tested—40
Insulation—class B
Temperature—"cold," or about 21 deg C
(With the exception of 3 values, all insulation resistances were 100 megohms or above. These 3 were 25, 38, and 50 megohms.)
Percentage of the machines failing to test up to the calculated values:
By Wieseman's formula using $K_s = 1.0$, the value given for good operation at 21 deg C............ 57.5 per cent
By the proposed A.S.A. formula $\dfrac{E}{\frac{\text{Rated kva}}{100} + 1{,}000}$........... None
By the proposed A.S.A. formula times 40...................... 22.5 per cent*

IV. Tests on Turbine Generators at the Factory:

Number of machines tested—13
Insulation—class B
Temperature—"hot," or about 75 deg C
(The lowest resistance was 15 megohms and all but one were below 100 megohms.)
Percentage of the machines failing to test up to the calculated values:
By Wieseman's formula using $K_s = 0.1$, the minimum value given for 75 deg C.................... 15.4 per cent
By the proposed A.S.A. formula $\dfrac{E}{\frac{\text{Rated kva}}{100} + 1{,}000}$........... None
By the proposed A.S.A. formula times 4.......................... 7.7 per cent*

* These values are all for higher voltage machines. This shows that the higher voltage machines have less margin under the proposed A.S.A. standard than do the lower voltage machines.

From the summaries of the megohm resistances given for each of the above group of tests, it is seen that all are sufficiently high to be quite safe. Practical operating experience bears this out. An extremely high insulation resistance may mean the insulation is very dry. It may still have voids, be brittle, or both, and therefore not be in good condition.

As indicated above, great variations in test values are found. These variations cannot be accounted for satisfactorily on the basis of insulation thickness and the area in contact with ground as is undertaken in this paper. A possible explanation of this is that unless the coils all have a good grounding material on their surface, the path for the resistance currents to ground may be very uncertain. The essential thing is that the insulation resistance be high enough to indicate a sufficiently dry insulation. We believe that the proposed A.S.A. formula meets these requirements when modified for a-c machines to state that the minimum value allowed will be one megohm. A simplification of the proposed A.S.A. formula for the insulation resistance of a-c armatures, which is more convenient and gives practically the same value, is:

$$\text{Megohms} = \frac{\text{Voltage}}{1{,}000}, \text{ with a minimum}$$

value of one megohm.

It is unfortunate that Mr. Wieseman has not included field insulation resistance in his paper. We believe that on large a-c machines this is of practically equal importance. We have collected data on a large number of machines and are convinced that this subject is well worth studying. It will be noted that all our data is based on tests at the factory. Operating engineers are in the best position to discuss what are safe and usual values and it is hoped that helpful data will come from this source.

R. E. Hellmund: During the early days of electrical machinery, a great deal of attention was paid to the measurement of the insulation resistance of new machines. However, the results obtained were so irregular that they did not seem to be of real practical value and therefore less attention was paid to these insulation measurements as time went on. More recently, however, the question has again been agitated, and Mr. Wieseman's paper as well as the study indicated by the discussions of Messrs. Henderson and Calvert and others are evidence of a somewhat renewed interest in this subject. Unfortunately, however, there does not seem to be available even now sufficient data and knowledge for formulating any rules that would be sound from an economical or operating point of view.

Mr. Wieseman in his paper makes an attempt to eliminate some irregularities by a uniform test procedure and to include some variables in his formulas, such, for instance, as a rough measure of the entire insulating surface. Although there is some logic in this, all the test data available plainly indicate that several other variables are of much greater practical importance than this insulating area; in fact, the test data indicate that there is practically no relation between such area and the results obtained. The formulas given take care of other variables by the proper choice of coefficients; these coefficients, however, vary over an exceedingly wide range. The amount of variation of these coefficients is entirely out of proportion to the variations introduced by the remainder of the formulas. It therefore would hardly seem advisable to introduce complications which at the present state of the art are not justified. With reference to the influence of the size of the insulating area, on the one hand it may be true that, everything else being equal, a lower resistance should be expected with increased area; on the other hand, it should also be considered that the larger the machines and the corresponding investment, the more desirable it is to increase the factor of safety. If some weight is given to this consideration and if it is fully appreciated that there are many uncontrollable variables, it seems that for the present there is a good deal of merit in the very simple rule suggested by Messrs. Henderson and Calvert for a-c armatures.

On the whole, however, I feel that before formulating any definite rules, we should establish a definite objective and devise a plan working toward such objective. If the insulation resistance is of any practical value in some or in all cases of machine windings, it is because it may ndicate the possibility of breakdown and service interruption. Therefore, if it can be established that there is a relation between these factors, both manufacturers and operators should be willing and anxious to make practical use thereof. The only possible way of arriving at any conclusion in this manner is through a collection of statistical data definitely inter-

relating insulation resistance measurements and breakdowns as well as the nature of the breakdowns. The latter item is of utmost importance. The data given by Messrs. Henderson and Calvert, for instance, seem to indicate that in the case of new a-c armatures, which usually have no exposed conductors, it is relatively easy to obtain a minimum insulation resistance of one megohm; it is furthermore quite likely that statistical data would show the danger of breakdown if the resistance of such windings reaches lower values. On the contrary, it is quite probable that statistical data relating to machine parts having a great many exposed conducting parts, and which therefore depend largely upon creepage distances, would show that the tested insulation resistance is of practically no value in giving any indication of the condition of the winding proper, although it may indicate the advisability of cleaning the creepage distances. In so far as the exposure of conducting parts cannot be eliminated in the case of commutators and slip rings, it may always be impracticable in these cases to resort to insulation tests for sizing up the operating reliability of the windings. Exposed conducting parts are also quite commonly used in connection with various types of field windings, and through facilitating ventilation and simplifying the insulation structure they have resulted in appreciable economies in design. The purchaser of these machines certainly would not be willing to pay higher prices for such machines, which he would have to do if such economies were eliminated, unless he could be definitely shown by statistical data that the lower insulation resistance which is likely to result from such designs actually indicates increased danger of breakdowns.

In view of these facts, I wish to emphasize again that the collection of statistical data, or the submission of such data by those who may have them available, and an analysis thereof should be the first step toward clarifying the issue. Unfortunately the manufacturers are not in a position to collect data of this nature and therefore must depend upon others for them.

W. B. Creagmile: There has been some feeling for a long time that A.I.E.E. Standards for insulation resistance of electrical machines were inadequate and in many cases gave too low a value for the resistance. Mr. Wieseman is to be congratulated on having developed workable formulas which take into account type, rated capacity, voltage, speed, and kind of insulating material of electrical machines. It is to be hoped similar research can soon be extended to other types of electrical equipment.

The following comments and criticisms may help to clear up what we believe to be a few rather important details, and in that way to stimulate a more extended practical use of insulation resistance tests for detecting and diagnosing insulation weakness.

Under the heading "Measurement of Insulation Resistance," p. 1011, it is stated:

"Insulation resistance of an armature winding may be measured with an instrument such as a megger, 'megohmer,' etc.; or with a voltmeter or a microammeter connected in series with the winding and a direct voltage. The megger has been used for many years, and it gives reliable readings if it is calibrated periodically and if it is operated long enough to eliminate the electrostatic capacity effect of the winding. With the voltmeter method, the maximum resistance that can be measured with reasonable accuracy is about 10 megohms when an ordinary voltmeter is used and about 100 megohms when a high resistance voltmeter is used. From the operator's viewpoint, however, a resistance above 100 megohms for any machine is considered satisfactory. The microammeter method is very accurate for measuring high insulation resistances if a storage battery furnishes the voltage."

We believe the author's reference to need for frequent calibration of megger instruments may be based on the use of instruments which have been in service for many years without recalibration, whereas voltmeters and microammeters are likely to be recalibrated frequently. It has been our experience that megger instruments hold their calibrations remarkably well, and do not need to be checked frequently.

Reference is made to an insulation resistance of 100 megohms being satisfactory from the operator's viewpoint. Accordingly, in practically all cases of testing the insulation resistance of electrical machines, a megger instrument having a range to 100 megohms will cover the requirements. Such an instrument has zero as the first point on the scale, with the highest numbered mark 100 megohms, and with infinity also marked. Such an instrument is self-checking at zero and infinity by operating on short and open circuits. If correct at these points, there is little chance for error throughout the scale. If it is possible to check the instrument on a resistance of 1 megohm and it is correct at this value also, there is almost no chance of error at any point on the scale.

The effect of electrostatic capacity on the testing instruments is not confined to the megger but appears also if any other type of ohmmeter, voltmeter, or microammeter is used. The megger will charge the electrostatic capacity at a slower rate than a storage battery, because of the small size of its generator and the use of a ballast resistance in series with the test circuit within the instrument. However, by shunting the ballast resistance of the megger during the first few seconds the voltage is applied the charging rate may be quickened very much. A 500-volt storage battery is seldom available, and for this reason, as well as convenience, etc., megger instruments have come to be considered standard for the testing of insulation resistance.

It is not intended to discuss values assigned to coefficient k as to whether they give too high or too low a value of resistance. The coefficients set down for conditions 1 and 2 of Table I at top of p. 1014 can be determined by tests on comparatively few machines. Coefficients for condition 3 and more particularly condition 4 must be determined by a long series of tests on many machines, and depend largely on the judgment of those who assign the proper values for insulation resistance. Condition 4, under which a machine should be cleaned and/or overhauled, is the one of greatest interest to the man who operates the machine.

We suggest that many plant electricians may find difficulty in working out the formulas given or in applying nomographs correctly, and we believe that recourse will be had to requesting the proper value of insulation resistance from the manufacturer, or failing in that, to resort to some relatively practical value such as one megohm. A "one megohm standard" has been set by many electrical engineers and plant electricians as sufficiently high for safe operation and not too difficult of attainment. It is higher than most values determined by the A.I.E.E. Standards except for high-voltage synchronous machines, and appears to have worked out very well in practice. Should one megohm prove to be too low in view of the values determined by the formulas given in the paper, a readjustment upward will probably follow in due time.

In the summarization of the paper (p. 1016), it is stated:

"The trend or slope of the curve of insulation resistance will indicate the condition of the insulation better than insulation resistance values themselves. If an insulation resistance curve of a machine is not available, insulation resistance obtained by the formula for conditions 3 and 4, Table I, can be used as a basis for comparison."

We understand the reference to be to what the author calls elsewhere an insulation resistance-time curve, extending over 10 to 15 minutes and similar to Figs. 1, 2, and 3 of the paper. These curves are very interesting, and the author's suggestion of how to use them in diagnosing the flow of current, whether due principally to moisture in the insulation and surface leakage, or absorption (see column 1, p. 1012), appears to be new and highly commendable. We would point out, however, that the curves shown are for very high values of insulation resistance—far higher than any values given in Tables II, III, IV, and V. Unfortunately, as illustrated in Fig. 2, the curve tends to become quite flat if the conduction and leakage currents are large compared to the absorption current. This is the case for such values of resistance as are determined by the formulas given in the paper, and the absorption current has relatively little effect. Consequently such curves are of little practical value to the man who wants to know if trouble is brewing.

Another sort of curve which is likely to prove even more useful (and which we thought at first the author might have had in mind) is a curve plotted for insulation resistance taken at periodic intervals such as one week or one month. Brief mention of such tests is made at the end of the author's summarization.

We believe thoroughly in periodic tests of insulation resistance and are backed up by the practice of many engineers who make such tests and record and plot values on cards properly ruled. Insulation tests are made only that we may know the condition of our machines. Consider the following cases:

Insulation resistance so low that operation is unsafe and something must be done to raise the resistance.

Insulation resistance low but well maintained. Machine is probably all right for operation, but an effort should be made to locate and remedy the cause of the low resistance.

Insulation resistance of fair or high value and well maintained. Machine should give little cause for worry.

Insulation resistance of fair or high value but showing a constant tendency toward lower values. An effort should be made to locate and remedy the cause and check the downward tendency.

Insulation resistance of fair or high value and previously well maintained but showing a sudden lowering in resistance. When this occurs, the machine should be watched carefully, and insulation resistance tests made at short intervals until the cause of the lowered value is located and reme-

died, or the resistance becomes steady at a lower value safe for operation, or reaches so low a value that the machine is unfit to be kept in service.

The paper recommends reading insulation resistance at the end of one minute electrification. It is worth noting, as shown in Figs. 1, 2, and 3, that there is an apparent increase in resistance for several minutes. Consequently, if in less than one minute the resistance of any machine is more than the value set for that machine, there is no necessity to wait until the end of any stated time interval before taking the reading unless records are to be kept for comparison, in which event all readings should be taken at the end of the same time interval.

E. J. Rutan: The paper on insulation resistance of armature windings is of particular interest in that the author is making an attempt to develop a suitable formula which will result in an insulation resistance higher than that at present required by the A.I.E.E. Standards. It is well known and considered rather peculiar that the formula at present approved results in a required insulation resistance far below that usually attained. The author's efforts are therefore to be commended in that he would require insulation resistances more in line with normal manufacturing practice on new machines. Although the formulas as developed may not be the most desirable way of expressing the limits to be attained, they are at least a start.

In connection with the constants for machines in service, I would like to speak with particular reference to synchronous converters. The formulas proposed still allow too low an insulation resistance for what would be considered safe operation. In general, the larger synchronous converters are used on systems where it is very undesirable to have failures from lack of proper maintenance. When insulation resistances as low as one megohm are permitted, there is considerable uncertainty as to when the resistance may suddenly become so low as to cause a flashover or failure. This is mentioned because on converting apparatus low insulation resistance is usually due to the collection of dirt or dust between exposed live parts and ground. A thorough cleaning and blowing out of the machine will usually eliminate this condition and bring the insulation resistance well above one megohm. Accordingly, in my estimation, any formula which provides a standard below that figure, is not suitable.

Of course it is known that insulation resistance is not a true measure of the condition of the insulation, but if regular tests are made and the trend is obtained the operator is well able to decide when the machine needs the necessary cleaning and maintenance.

The last paragraph of the author's summary gives the necessary information for determining the condition of insulation and the desirable method of using insulation resistance information.

J. L. Rylander: Mr. Wieseman's paper is a desirable addition to the subject of insulation resistance, on which comparatively little information has been published. The curves showing the variation of resistance with the time of appilcation are new and

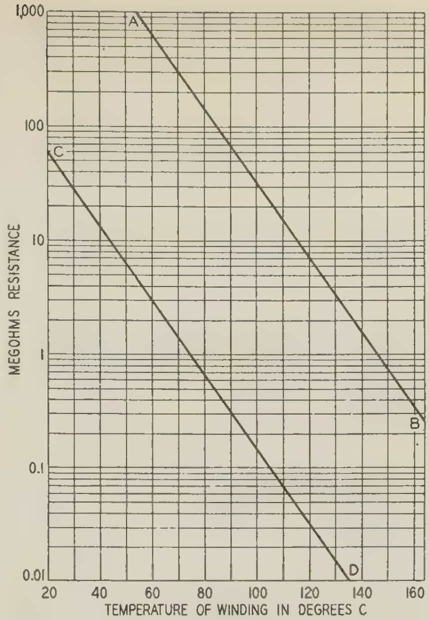


Fig. 1. Variation of insulation resistance with temperature

bring out clearly another of the several variables encountered when dealing with this subject.

However, the suggested formulas with their different fractional exponents and their different values and the nomographs do not eliminate any one of the major variables. Furthermore, these formulas are complicated, whereas the present formula is quite simple and probably more accurate.

The constants chosen by Mr. Wieseman for his formulas are so different from each other that it would be difficult to have confidence in them. For example, the constant for class *B* insulation in Table I is 188 times as great as for class *A* insulation for No. 4 condition. It would be difficult to choose a constant for those machines which have a mixture of class *A* and class *B* insulation materials, such as those that use class *A* insulation plus mica. There does not appear to be any consistent relationship among the many different "constants."

Although the value of insulation resistance is affected by the size of machine, the kind of insulating materials and their quantity, the variations due to these factors are comparatively small when compared to the 3 major factors that are always involved. These 3 are: (1) the temperature of the insulation; (2) the moisture or solvent that is present in the insulation; and (3) the conducting dust and moisture on the surface of the insulation. Any one of these factors is such as to change the insulation resistance value 10 times or 100 times and in some cases even 1,000 times. As the chief purpose of insulation resistance is to determine the extent to which the insulation has been affected by these latter 2 conditions, it seems quite logical that the other great variable (temperature) should always be given the chief consideration when using insulation resistance values.

The straight line curves shown in Fig. 1 of this discussion, obtained from test data, show the manner in which insulation resistance changes with temperature on a particular line of general purpose squirrel cage induction motors. The upper line *AB* shows what the insulation resistance usually is on clean and very dry windings, and the lower line *CD* shows about what the same windings measure if they are filled with unbaked varnish with solvent in it, or if the windings have been soaked in water for a certain time. Intermediate stages of dryness are shown by straight lines parallel to and between these 2 lines.

The formula as proposed by the A.S.A.,

$$R_i = \frac{\text{Rated voltage}}{\dfrac{\text{Rated kva}}{100} + 1{,}000}$$

gives the same values for all ratings up to 1,000 kva as the more simplified rule often used by many:

$$R_i = \frac{\text{Rated voltage}}{1{,}000}$$

Even for a 10,000-kva machine this simplified rule gives practically the same value as the A.S.A. formula. A 100,000-kva machine only doubles the value and that is only a trifling quantity when discussing insulation resistance. It is desirable to have a larger factor of safety on the larger machines. A formula $R_i = \dfrac{\text{Rated voltage}}{1{,}000}$ at a definite temperature such as 75 deg C and a chart like the curve in Fig. 1 of this discussion to make corrections for all other temperatures at which the measurements were taken would be a very decided improvement over the existing formula and methods.

Split Winding Transformers

Discussion and author's closure of a paper by D. D. Chase and A. N. Garin published in the June 1934 issue, p. 914–22, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

P. L. Alger: It appears to me that Messrs. Chase and Garin's paper is particularly interesting as a specific example of progress in a field that has yet been relatively little developed. Since the first important application of the split winding idea in the design of double winding turbine generators some 6 years ago, this scheme has also been employed extensively in starting synchronous motors. Many special winding arrangements have been developed for this purpose. In general, the winding is arranged in 2 or more similar circuits, only one of which is thrown on the line at a time so that the motor can start on full voltage with low current and then be put into operation in one or more additional steps by successively throwing on the other winding sections in parallel with the first. This scheme avoids opening the motor circuit at any time during the starting period, and also avoids the use of any compensator or reactor.

As yet, however, the system has not been used for generators aside from the turbine type. It seems probable that in some of the older low voltage systems the existing

generators could be advantageously reconnected for double winding operation, obtaining increased reliability of operation and reduction of switching capacity requirements. A review of the advantages of split winding transformers described in this paper and those for generators previously described, together with the realization that these advantages can often be obtained in existing systems by relatively inexpensive changes, may lead to a desirable expansion of the split winding system's usefulness.

H. L. Cole: The paper by Messrs. Chase and Garin is particularly interesting to the transformer designer because it points out some of the natural limitations of this type of transformer, as well as a summary of its general application.

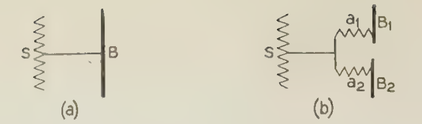
In the early days of transformer design it was common practice to split a high capacity or unusually heavy current winding into 2 or more parts and carry the separate circuits to the outside of the case through separate pairs of terminals. This was advantageous because it simplified the coil design and permitted the use of a smaller and less costly terminal arrangement. In extending the separation of the circuits farther than the outside of the transformer terminals, into the station bus and outside the station on separate lines, 2 things must be considered by the transformer designer: (1) the effect of transfer reactance and load unbalance on the losses and heating of the transformer; and (2) the necessity for completely insulating each circuit and making insulation tests (including impulse tests) on each one.

Seven years ago a 94,000-kva bank of transformers for the Colfax station, Duquesne Light Company, was supplied with the split winding type of circuit, to reduce the size of breakers required.

An interesting installation made in 1930 of a 90,000 kva bank, at the Roseland switching station of the Public Service Electric and Gas Company, is described in the Feb. 21, 1931, Electrical World. ("Design Features of the World's Largest Transformers," H. L. Cole and F. J. Vogel.) In these transformers the split windings are for 138,000 volts; they have a high ratio of transfer reactance to through reactance and a comparatively high permissible load unbalance. Various methods of obtaining interlacing and interleaving of windings are described in this article. Many other transformer installations of the shell-type interleaved-coil design, which is particularly suitable for obtaining desired reactances, have been made with split windings.

A. Boyajian: Steinmetz used to lecture on "the serious problem of huge concentrations of energy in short circuits." Little is heard on the subject nowadays because the problem has been solved to a large extent by the split winding generator suggested by Mr. Chase and Mr. Barton, the split winding transformer suggested by Mr. Brand and Mr. Gay, and improved breakers.

As the authors have covered the split winding transformer very thoroughly, I wish to add a few words on how transformer windings or busses and transmission circuits



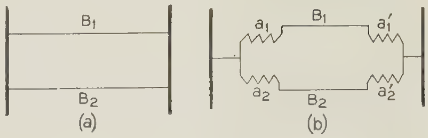


Fig. 1(top). Transformer secondary feeding bus

Fig. 2(bottom). Sending and receiving busses connected by a double transmission circuit

which were not originally split or sectionalized can be split or sectionalized externally by what might be called a sectionalizing autotransformer.

In Fig. 1*a* is shown the one-wire diagram of an unsplit transformer secondary S feeding an unsplit bus B. In Fig. 1*b* is shown this system sectionalized with the aid of a sectionalizing autotransformer having the windings A_1 and A_2 wound so that "through" currents (i. e., from S to B_1, B_2, or from B_1, B_2 to S) flow through A_1 and A_2 noninductively, but "transfer" currents between B_1 and B_2 flow through A_1 and A_2 inductively. Thus, with such an arrangement, the "through" reactance of the system need not be materially affected, but the "transfer" reactance may be adjusted to any desired value. The magnetic circuit of A_1 and A_2 should not saturate under short circuit, neither should the "transfer reactance" be excessive at normal load unbalances. This means that the core should either have an airgap or be altogether nonferrous.

In Fig. 2*a* are shown sending and receiving busses connected by a double transmission circuit. In Fig. 2*b* is shown the transmission system sectionalized by 2 sectionalizing autotransformers, one at each end. Power flowing in lines B_1 and B_2 in the same direction flows noninductively through the autotransformers, but any exchange power between B_1 and B_2 encounters high "transfer" reactance through the autotransformers, and thus short circuits in either transmission circuit are limited to far smaller magnitudes than what would otherwise correspond to the system impedance for normal currents. If power can be fed from only one end of the system, sectionalizing need be done at only that end, but if power can be fed from either or both ends, than both ends are preferably sectionalized.

The size of the sectionalizing unit as a 2-winding transformer in per cent of the base kva will be of the order of a quarter of the per cent transfer reactance, if the base kva for the percentage value of the reactances is the total output of the busses and each section is rated at half of the total. Thus, in Fig. 1*b* let S be a 100,000-kva source, and B_1 and B_2 each 50,000-kva loads. If the transfer reactance contributed by the autotransformer is 50 per cent based on 100,000 kva, the physical size of the autotransformer as a 2-winding transformer will be of the order of 12,500 kva—a pretty husky fellow. This shows that if the transformer or generator is originally sectionalized by proper foresight, a large portion of the cost and losses of the external sectionalizing device would be saved. We say "a large portion" and not "all" advisedly, inasmuch as the addition of this large extra duty on the transformer may not be obtained without increased complication and cost.

An advantage of the external sectionalizing autotransformer is that with it any desired ratio of "transfer" to "through" reactance can be obtained without serious design difficulty, whereas in a split winding transformer, as this ratio increases beyond a value of 4, design difficulties increase with it.

Of course, if the source of power consists of a number of generators or transformers operating in parallel, sectionalizing can be accomplished in simple well-known manners, with or without bus sectionalizing reactors.

A. N. Garin: The "sectionalizing autotransformer" proposed by Mr. Boyajian may be appropriately called a "split winding reactor." It possesses all the reactive characteristics of a split winding transformer; its "through," "transfer," and "one circuit" reactances are readily identified and must satisfy eq 2 of our paper.

It is more convenient, however, to deal with overall impedances of the power transformer and the "sectionalizing autotransformers" taken together, in which case all the formulas and curves of our paper will become applicable.

It has been stated in our paper that when 2 separate lines are connected through reactors to the same terminals of an ordinary transformer the total theoretically possible range of values of the ratio of "transfer" to "through" reactance is contained between the limits of zero and 4. These limits apply when separate reactors are used. The upper limit can be raised, however, by providing inductive coupling, of proper sign and magnitude, between the 2 reactors. This can be done either by means of auxiliary coupling windings on the 2 separate reactors, or by interwinding the 2 reactors together. The latter method would give us a device proposed by Mr. Boyajian under the name of "sectionalizing autotransformer."

The practicability of "sectionalizing autotransformers" for moderate voltages and in moderate sizes is demonstrated by their frequent use in load ratio control transformers under the names of "preventive autotransformers" and "circulating current limiting reactors." The ratio of "transfer" to "through" reactance required for load ratio control application is, however, usually less than one. This explains the difference in size, and consequently cost and losses, between the modest load ratio control reactor and the "husky fellow" visualized by Mr. Boyajian.

H. L. Cole has given a very interesting historical review of the development of split winding transformers beginning with "the early days of transformer design when it was common practice to split a high capacity or unusually heavy current winding into 2 or more parts and carry the separate circuits to the outside of the case through separate pairs of terminals." We might begin perhaps with a still earlier date—the date when multiple connected strands were first used

in transformer windings. I should like to point out, however, that neither transformers with windings consisting of several strands connected in multiple below the transformer cover, nor transformers with windings consisting of several circuits brought out separately through the cover, but connected in multiple at the bus, are split winding transformers in the modern meaning of this term. With parallel circuits, as with parallel strands, the only problem confronting the designer is to obtain approximately equal current division—and as a rule this does not require either large or, as pointed out in the paper, symmetrical reactances.

In regard to the early installations of true split winding transformers, I was interested to learn of the 7-year old Duquesne Light Company transformers. Another early installation is a 66,667 kva autotransformer of the Buffalo General Electric Company which was installed in 1926.

I regret having overlooked the very interesting *Electrical World* article by Messrs. H. L. Cole and F. J. Vogel. From its title one would not expect it to contain the information on split winding transformers it does contain. This article shows that Roseland transformers have a ratio of transfer to through reactance equal to 8.7 and the maximum permissible load unbalance is given by the load division of 40//60 per cent. As Mr. Cole has stated, the permissible load unbalance is comparatively high, considering the high ratio of transfer to through reactance. That still higher values of reactance ratio can be obtained, when necessary, together with still greater permissible load unbalance is shown by the 66,667 kva Brooklyn Edison autotransformers mentioned in our paper, which have a reactance ratio of 13.1 and 34//66 per cent permissible load division.

Mr. Cole's endorsement of statements in our paper concerning the effects of transfer reactance and load unbalance on load losses and concerning the necessity of insulating the circuits of a split winding as if they were separate windings is highly gratifying. Mr. Cole would hardly expect me to agree, however, that shell type construction, which limits the designer to interleaved coil groupings, can possibly be more suitable for obtaining desired reactances than the core type construction, which offers the designer the choice of interleaved, concentric, and mixed interleaved and concentric coil groupings.

P. L. Alger's discussion is valuable in pointing out the spread of the "split winding" principle of construction among various types of electrical machinery. The process is far from being completed and undoubtedly new and unexpected applications will be found. It would be interesting to survey the fields of steam, hydraulic, and other nonelectrical machinery with a view to introducing the "split system" principle. We might learn, however, that mechanical engineers were the first to apply this principle.

Returning to electrical engineering, the concepts and methods developed for the study of split winding transformers may be found applicable and illuminating in apparently unrelated fields. As an example, a symmetrical 3-phase system may be considered as a system split into 3 circuits. The "through" load, with definition modified to permit the angular displacement of the 3 phase currents, is given by the positive phase sequence currents. There are 2 "transfer" loads, represented by negative and zero phase sequence currents respectively. The 1 "through" and the 2 "transfer" impedances are readily identified as the impedances offered to the flow of positive, negative, and zero sequence currents. Thus the ability of the 3-phase system to carry unbalanced loads, its performance under unsymmetrical faults, etc., are seen to be analogous to the characteristics of split winding transformers.

Encouraging Initiative in the Engineering Student

C. L. Dawes, June 1934 issue, p. 910–4.

Industry Demands and Engineering Education

L. W. W. Morrow, April 1934 issue, p. 518–22.

Engineers of the Next Generation

C. F. Hirshfeld, June 1934 issue, p. 857–9.

Discussion of a group of papers (and author's closure of one paper) presented for oral discussion at the session on education at the summer convention, Hot Springs, Va., June 26, 1934. (Discussion and closures of individual papers of this group are given under separate headings on later papers.)

P. L. Alger: These 3 papers seem to me most significant of a fundamental change that is taking place in technical education. Each of them expresses in a different way the broad conception that we must seek out and teach the fundamentals of engineering knowledge.

Professor Dawes emphasizes the necessity for developing initiative and self-reliance of students. Self-reliance, however, comes only from ability to handle new situations, which implies a thorough grasp of the fundamentals of knowledge common to most engineering problems.

Mr. Morrow stresses the need for giving the business man an understanding of engineering, so that the broad planning which he is responsible for will be more intelligently done. This again requires the selection and presentation to the students of the essence of engineering knowledge.

Mr. Hirshfeld appeals for common action in defining the requirements for engineering proficiency and evaluating the existing curricula. Here also the first step must be to define the fundamentals of engineering knowledge.

Dr. Steinmetz once said that early in the process of learning, each additional fact is more difficult to retain than the last one. Finally, however, some favored people reach a stage where new knowledge becomes successively easier and easier to acquire, due to their appreciation of the interrelations of facts, and to such analogies as those suggested by the periodic table of elements. I believe we have now reached this critical stage in engineering education as a whole. We should teach knowledge as a single subject, not as a series of disconnected courses carried to widely different degrees of refinement.

So far as possible, knowledge should be acquired in the same manner that the successive terms of an infinite series are developed, each term being logically developed from the preceding one, and each representing a higher degree of specialization. We do not learn to swim by taking a lecture course on the proper arm motions and then waiting a couple of years before entering the water. Nor should we take a mathematics course without concurrently putting the mathematics to practical use.

I think that the mathematics should be taught as though it were nothing more than a shorthand for describing the physical realities, the same expressions being representative of a wide variety of natural phenomena. By training the student at each step to translate from the mathematics to physics and back again, most of the basic essentials of all types of engineering should be acquired in a single course.

Also, economics should be so taught that the student will regard all history as a laboratory report of the results of a series of experiments, by analysis of which he must determine the causes and effects of all human actions. The laws of ethics as well as those of finance may be developed by study of economic data just as the laws of gases have been developed by physical and chemical experimentation.

If these 2 subjects of mathematics and economics can be so intimately related to the student's own observations and actions that he instinctively collects all available information and arranges it in mathematical form before reaching a conclusion, that student will be well fitted for an engineering career.

E. E. George: In this most interesting symposium on engineering education nothing has been said about costs or economics. It seems to be generally assumed that an engineering education is always worth what it costs, and that we need not consider whether or not the cost of production is reasonable and whether or not the selling price is at least equal to the cost of production. Yet the cost of education of all kinds has risen with great rapidity, and recently there have been wide-spread and well justified criticisms of the cost of schooling, even in the grammar school grades. Certain educators have seemed to think that parents should pay anything requested for tuition, textbooks, or school taxes, so long as the request was made in the name of *education.* Perhaps these current discussions about engineering education will result in the engineering student getting more nearly the worth of his money.

However, the suggestion to add another

year or 2 to the present 4-year technical courses seems to the writer to be a step in the wrong direction. Such a move tends more and more to restrict education to the children of the wealthy, yet very few argue that boys from families of wealth would make the best engineers or would be more satisfied in their profession. The coöperative engineering courses offered by certain schools have considerable value, enabling each student to earn part of the cost of his education, aside from their value in orienting his perspective of engineering work in general. Some course should perhaps be set up whereby the student could attend school for 2 or 3 years and then, after a year or 2 of work in the field to replenish his finances, go back and finish his professional course. This would mean less rearrangement of class schedules and courses than in the present coöperative courses in which students change every 6 weeks.

There are today many occupations where some technical knowledge is essential but where a limited amount may be reasonably satisfactory. There should be courses of 2 or 3 years which would give a man some practical technical information, even though they do not qualify him as a professional engineer. At present the engineer who completes only part of the 4-year course has no definite standing, no diploma, and has not acquired any correlated technical education of consequence. The manual training school idea has never taken hold much in this country, but there are lots of men with some practical experience who would be worth much more to themselves and to their employers after a year or 2 of technical engineering education in fundamental principles. Because the educational system of today offers nothing of this kind, many large employers try to train their own men. This in itself indicates that the educational system is falling down on the "industrial" end of the job.

The Institute was favored with some very fine addresses on the duties of the professional engineer, and of the attitude which the successful engineer should have, but one cannot help wondering if these idealistic professional concepts would be received in the proper spirit by those engineers just out of school who are out of jobs or who are working at meager wages in the name of "getting experience." Those of us further along in our professions, who belong to the A.I.E.E. and come to the conventions, undoubtedly approve of the ideals outlined by some of the able speakers who addressed us on professional education, but it is a recognized fact that material prosperity must precede cultural advancement. Much has been said about getting the young engineer properly started off in his career, about giving him the right outlook upon life, and about raising the prestige of the engineering profession, but nothing would do quite as much toward raising the prestige of the engineering profession as an organized effort toward giving each young engineer interesting technical work at a rate of pay commensurate with the value of his work and with the investment he has made in his education. As long as certain of the older engineers regard it as unethical for an engineering society to discuss salary levels and working conditions, just so long will the younger engineer regard his profession with some doubt and lack of confidence. Instances have been reported in certain sections of the country where technical engineers never had a Saturday afternoon off, until the NRA code came along, and other instances where young engineers' weekly pay was increased by NRA minimum wage requirements, yet the NRA was intended to help only the unskilled and uneducated. Some of the worst offenders among employers have been engineers who hold responsible positions and who are in a position to effectively determine salaries and working conditions for younger engineers reporting to them.

Perhaps the Engineers Council for Professional Development will give earnest consideration to some of these things and acquire enough publicity that engineers in general may know what is being done. Until this is done the engineers will continue to be split into 2 distinct groups: a few conservative "elder statesmen," deans, professors, and consulting engineers, who believe in unrestricted competition among engineering graduates and a "closed corporation" for professional engineers; and a large number of young engineers more or less dissatisfied with the organization and operation of the engineering societies, with some of them entirely radical in their economic views and likely to support any movement or organization that promises to improve their economic condition, regardless of technical achievements, social ideals, or other long-range interests, of which the A.I.E.E. is justly proud.

R. W. Sorensen: The 3 papers relating to the subject of an engineer's education are, indeed, most interesting. Taken together, they present thoroughly the many ideas which bear upon what we, as electrical engineers, are trying to do to keep abreast of the progress in today's civilization and to train the younger men who will carry on the torch of our profession in ways which we think will best enable them to attain the results we so much desire. We, naturally, are trying to develop our ideal engineer; and in so doing have set standards which, if met completely, will produce supermen who will push all of us out of our jobs. As engineers, we have learned to write specifications for everything with which we have to deal; and we are now writing a specification for an engineer.

In the preparation of this specification we are, I gather from these papers, doing very well, but are encountering 2 major difficulties, namely: insufficient attention to the raw material of which the engineer is to be made; and the endeavor to make our specification an all-inclusive one, covering in the one specification all the general and special requirements of engineers. The first difficulty must, of course, be overcome largely by our educational institutions, many of the professors from which are with us this morning, by the simple process of paying more attention to the prospective student in his pre-college work and the application of more rigorous selective methods through which the candidate must pass to be admitted to our engineering colleges. The use of rigorous selective methods for entrance to college is, of course, very difficult if we consider an engineering course as a part of our regular public educational program and work on a basis that every one who completes a high school course is entitled to admission to some engineering college. Practicing engineers can give much aid to those of us who are doing the teaching and are advocating rigorous selection for entrance to engineering colleges by spreading the gospel of what E.C.P.D. plans to do among the youth of pre-college days, and by recognizing the fact that no college can make an engineer who will come up to the specifications we are discussing this morning if the material with which the college must work is not of the very best quality. In our specification for an engineer, about which I am not at all pessimistic because I have great hopes that we are rapidly approaching a time when the members of our profession will very closely meet it, we are, as I have mentioned, setting very high standards because, as you will note, we have demanded that, first of all, the engineer be a highly qualified specialist in any line of engineering endeavor that may come his way even though he is assigned, perhaps by chance, to some phase of engineering work to which, previous to the assignment, he has paid little attention. In doing this there is grave danger that we are too forgetful of the fact that each year we are adding new developments which we expect the young engineer to know, even though we have kept him busy during his college course cramming into him the accomplishments incidental to the past history of our profession. Again, we are demanding that the young engineer must know how to converse intelligently with his fellow citizens concerning art, literature, music, health, biology, geology, religion, and many other things of interest to human beings. We expect him, in his conversation, to show that he is a thorough master of at least one language and, better, he should know several. In addition to meeting these requirements, we expect him to be a good dancer, a good bridge player, good at golf and badminton, with perhaps a few extras thrown in, and, above all, he should have in his make-up enough of the soul of a researcher and love for pure science to make him willing, after having become qualified in all the things named and many more, to forget them and retire to a sub-basement room in some laboratory and toil many hours per day, day after day, week after week, and month after month on a pet research problem.

Then, because our engineer must live and may have a desire to support a family, we expect him to come out of his sub-basement laboratory with his research problem applicable to some practical need. With this accomplished all he had to do is find a way to finance and secure patents which will protect his findings and contact some industry that will find a market for what he has developed. Of course, to do this and be sure he has good patent protection, he must develop, incidentally, a fine knowledge by patent procedure.

You may say these comments are exaggerated and visionary, nevertheless they are practically the demands which we are setting up in our specification for an engineer and which we hope to have met to a considerable degree. Moreover, remarkable as it may seem, these demands are met to a very large degree; and so great is our expectation of having them met that

I know of college groups which rather recently have spent many hours discussing ways and means of enabling students to meet all these demands. The magic words which initiated these discussions were: "Their technical training is most excellent, but they are failing in the broad knowledge of human qualities including social relationships and in economics," which words are almost the same as one phrase in the paper by Professor Dawes.

After a committee consisting of very able business men, faculty members, members of a board of trustees, alumni members, and students of the college in question had devoted much time and thought to the analysis of these problems, a few minor changes in the program carried on by the college under discussion were made. These changes may be summed up in 2 recommendations: the appointment of a committee to plan more opportunity for students to participate in social functions; and a change in academic rules permitting to continue and remain in good standing seniors who, at the end of the first or second term of their senior year, have not made the usual minimum requirements for continuation in college. It is understood, of course, that these seniors must bring all their work up to the required minimum standard before graduation.

Perhaps the puzzling question as to length of course will be decided some day by a new arrangement whereby the better students in a group being trained for certain routine engineering work will be moved on to courses involving theory and mathematical applications, and the better ones from this group in theory will be moved on to a course of more advanced work including research. Until that time has arrived, it would seem to be rather dangerous for us arbitrarily to divide engineering schools into groups as suggested by Mr. Morrow, some colleges devoting their entire time to training for routine work, whereas other colleges would be devoting their entire attention to the courses more theoretical in nature.

Specifically, Professor Dawes's paper is largely of value in a psychological presentation of choice to the student as I find that his so-called wholly elective curriculum is, after all, very similar to the curriculum at California Institute of Technology, with which I am most familiar and which, for undergraduate work, is almost wholly prescriptive. That is, it seems to me that Mr. Dawes's plan as outlined, is very much like the modern kindergarten and grade school courses which are advertised as being arranged to allow the pupil full freedom of choice as to what will be done. For example, recently I have been made aware of the fact that one morning a certain group of children in a school of this kind suddenly decided that they would like to visit a dairy, and on another morning they suddenly decided they would like to visit a dining car to see how meals were served on a train. On both these occasions, within a very few minutes after the children had reached their decision, automobiles for transporting them to the place they wished to see were on hand and, when the children arrived at the dairy and at the dining car, respectively, they found the most interesting operations of these 2 institutions at just the right phase to be most interesting to them. Moreover, suitable refreshments in the way of cookies, fruits, etc., were on hand in order that each child might take away some pleasing souvenir of the trip.

In conclusion, my opinion therefore is that whether we consider our courses prescriptive or wholly elective, we have, for the most part, in all our better colleges, arranged courses which represent the best composite methods of engineers and teachers alike for teaching those who will, in the next generation, solve engineering problems in a way best suited to the convenience and service of mankind.

W. H. Timbie: Mr. Morrow presents a most timely discussion of the question that is of utmost importance not only to engineering educators, but to every one interested in higher education in all fields. Although he has not stated it in so many words, the whole import of his analysis is that engineering education is rapidly becoming, if in fact it has not already become, the liberal education of today.

By liberal education I mean that kind of an education which sets as its goal the development of the latent interest and potentialities not only of each individual, but also of the social organism of which he is a member. In other words, it is an education which will give him a correct understanding of the spirit of his own generation, and will best enable him to fit into the era in which he is to live, and to take his part in advancing civilization.

This has been called the Machine Age, or the Power Age, but in spite of all the machinery and the power, the spirit of the age is scientific, and in the highest degree, idealistic. Mr. Morrow's paper is a well founded plea further to liberalize engineering education by seeing to it that not all the student's time is devoted to the study of machinery and power, but that some time is devoted to the study of "what it is all about" . . . of history, philosophy, and economics. I heartily agree with him as to this need, but a word of caution should be introduced at this time to emphasize the fact that the greatest care must be used as to *what* history, *what* philosophy, and *what* economics should be taught, and the manner in which they should be taught.

For example, Latin and Greek used to be considered as liberalizing subjects. Sometimes they were, but more often they were merely mental exercises. The subjects of history, philosophy, and economics are particularly susceptible to the use of poor material and to wrong viewpoints and methods of presentation. To my mind there is little that is liberalizing in historical exposition that deals almost exclusively with less than 10 per cent of the people of a given generation—its kings, queens, and military leaders—or in philosophy that is merely a history of the different philosophies of the world, but does not develop in the student a wholesome philosophy of his own, or in economics that is deductive and speculative rather than social and factual. To be truly liberalizing a course in economics should be "social economics," and I believe it should be taught by an engineer—one who has analyzed modern engineering problems from their social and economic aspects, and who uses on these aspects the same rigorous scientific thinking and methods of attack that he employs in the solution of so-called technical problems. History should be studied for the light it will throw upon the path of civilization up to the present time. One of the surest guides for the future is the knowledge of how we arrived at our present position. For this reason history should be taught not in detached units, but as a comprehensive whole. It should not be military history, civil history, and economic history, but a synthesized study which presents the combined effect of all factors, foreign and domestic, upon successive eras of the world's history. Here again the teacher and the method of presentation are fully as important as the material studied.

Finally, while I agree that there is need of liberalizing all engineering curricula by the introduction of these important subjects, properly taught, there is also, I believe, an equal need to add to the little groups of Mr. Morrow's specialists still another group whose tastes and abilities lie in this field of social economics. The members of this "economics" group should receive intensive training in the art of navigating the "ship of industry." They should be given all the preliminary training possible to enable them eventually to reach their place on the "bridge." The increasingly large number of "captains of industry" who have been drawn from the ranks of these other groups of specialists proves that the type of training which these groups are receiving is conspicuously effective in preparing them for positions of leadership and responsibility. To add this other group would only be adding another possible route to the top. However, to train members of this new group for their positions of leadership, there is needed not a curriculum in which a few milk-and-water courses in economics, business methods, and industrial management are superimposed upon a smattering of engineering subjects, but rather a thorough and rigorous engineering training, with special emphasis on an equally rigorous application of scientific habits of thought and engineering methods of analysis to modern social and economic problems. If Mr. Morrow's plan contemplates this latter type of course, I believe it is right in line with the present trend of engineering education.

Professor Dawes's paper on "Developing Initiative in the Engineering Student" is also timely. The idea of putting a student more on his own, especially in the laboratory, as to what he will do and as to how he will do it has been in operation at M.I.T. with gratifying results for several years. It was first tried out on selected groups of students and gradually introduced as our regular practice. We go even much further than this. We believe that every part of a student's career should be so conducted as to develop not only his initiative and originality, but also a proper sense of his own responsibility in planning out not only his laboratory work but his entire career. For this reason, in the electrical engineering department we really have no standard curriculum but each student has his own individual program of studies of an exacting character and in logical sequence. This means that we have about as many curricula in electrical engineering as we have students. The cur-

riculum printed in the catalog is merely a guide to show the student how to build up his own course of studies. Eight times a year a student officially presents his program to his registration officers for their criticism and advice. Unofficially, I imagine, the student at all times is seeking information and advice not only at the Institute, but also in industry and in business, concerning everything that pertains to an engineering career. In other words, each student must be aiming at some definite goal and must give serious consideration to a plan for getting there. Of course as he gets more acquainted with the industrial and commercial fields, and with his own special abilities and individual preferences, he may from time to time make slight changes in his objective and in the method of arriving at it.

This means that a student has a wide choice in the subjects which he may study, but it does not mean that he can scatter all over the field and get only a superficial knowledge of engineering as a whole. There is a main stem of mathematical physics related to electrical engineering which he must follow, but he has a wide choice as to the field in which he chooses to study the application of these principles, and as to what subjects he wishes to take in order to buttress and strengthen his main stem. For instance, a student who wishes to specialize in electronics will study exactly the same theory as the student who is specializing in electromagnetic machinery. He would, however, choose his courses so that the applications of the theory were to electronic devices rather than to rotating machinery. Similarly a student who is interested in the economic aspects of engineering has an opportunity to select courses which emphasize this aspect. By this procedure, students are not only encouraged but actually compelled throughout their entire course to give thoughtful consideration to their objects in being at M.I.T. and to the methods of obtaining their objectives.

Finally, I cannot resist the temptation to question Professor Dawes's reasons for selecting the titles which he has included in the bibliography at the conclusion of his paper. To be sure they are pertinent and well worth reading, but why pick out these few articles which deal more or less with the details of administration and instruction rather than with the larger fundamental considerations? Probably, these fundamental principles having been laid down as far back as Plato and Aristotle, it was because the literature concerning them extends from classic times down through Pestalozzi, Ascham, and Bacon, to John Dewey of our own day, and a comprehensive list would have been altogether too long.

C. F. Hirshfeld: The discussion offered by Mr. E. E. George touches a subject to which I have given a great deal of thought, particularly during the past 5 years. What he says about the economic value of an engineering education and about the economic status of the engineer represents a viewpoint and state of mind that is very common at present.

I think it necessary that we first distinguish clearly between temporary phenomena due to the existing depression and more permanent phenomena which are characteristic of both boom and depression periods. It is natural that during a depression there should be a surplus of engineers. A large part of the profession is necessarily employed in the creation of capital goods as against consumer goods and it is characteristic of a depression that the production of capital goods reaches a very low ebb. Men thus thrown out of normal employment are necessarily going to work for what they can get at any job that they can get. We must not allow such conditions to befog our thinking when considering the broad question of the economic status of the engineer. This would be just as foolish as would be the determination of normal farm incomes by studying the present incomes of farmers in the drought stricken areas of this country.

It is possible to speak with some knowledge of what may be called the normal economic status of the engineer. The A.S.M.E. has had a committee studying that subject for some years and several comprehensive reports have been published. One outstanding finding is the tremendous range of annual earnings among engineers. The committee found that those engineers whose activities indicate that they combine a knowledge of engineering with business or executive or administrative abilities receive by far the largest incomes as a class, while those who are capable of doing only routine technical work are as a class most poorly paid.

My own interpretation of the findings of the committee is that they represent exactly what one would expect. There is in this country a comparatively small number of outstanding men with engineering training. Those men can command, in one way or another, large annual incomes. At the other end of the scale there is a very large number of individuals with engineering training who do not possess any outstanding characteristics. Any one of them can be replaced easily and quickly with another man of equal training and ability. These men cannot earn large annual incomes because of the ease with which they can be replaced. They are really in a marginal position. Between these 2 classes lies a widely spread third class, the best members of which touch the upper class and the poorest of which touch the lower class.

I feel that we must recognize such a distribution in the engineering profession not only as fact but as a natural fact which cannot be changed. It parallels the conditions in all other walks of life. To rail against it is futile and to attempt to change it by law or otherwise is fruitless. It simply represents the general distribution of abilities in the human race.

There is the possibility that the incomes of engineers can be shifted upward as a class. This is indeed the only real hope for improving the economic status of those in the lower earning groups. But, if this is to be done, the engineers must so improve themselves as servants of the public that that public recognizes the fairness of higher compensation. This is one of the thoughts that lies back of E.C.P.D. which, as a matter of fact, is an outgrowth of one of the recommendations of the A.S.M.E. committee on the economic status of the engineer. It is thought that as engineers as a class succeed in adding to their present technical engineering knowledge that further insight into human affairs, economic and social, which E.C.P.D. is providing for, these better equipped, more rounded, and more human engineers will automatically command greater incomes because of their greater degree of usefulness. Even then, there are bound to be some for whom such disciplines are too severe. These will unfortunately remain as a dissatisfied substratum whose heritage, through no fault of their own, does not fit them to rise above that level. This reads like a hard philosophy. It is a hard but a pragmatic one and, if the engineer stands for any one thing, it is a recognition of facts as demonstrated by experience.

I believe that it is also necessary that we recognize another set of facts. We are all inclined to form false estimates of the earnings in other professions. We look at the successful lawyer, the successful doctor of medicine, or the outstanding religious leader; we visualize their probable incomes and we compare these exceptions with our averages or even our lowest. Seldom do we compare like levels or true averages.

If we believe that as engineers we are in an unfortunate economic position, we can certainly derive comfort, if not satisfaction, from properly made comparisons. For example, the graduates of the better schools of medicine are now required to spend 8 years in college and then to work as internes for 2 years without compensation other than room, board, and laundry before they are in position to begin practice. Is the young engineering graduate who starts at $25.00 to $35.00 a week after 4 years of college so badly off as he thinks when compared to the young medical practitioner? Moreover, statistics show the same sort of spread of annual earnings in the medical profession as we find in engineering. The average annual earnings of doctors of medicine have been shown to be small indeed when compared to the investment in preparation for a medical career.

I think we must conclude that in the long run that which one is paid represents very closely one's worth to the community and, if we do so conclude, it follows that our pay as a class can be increased only as we not only prepare ourselves to be of greater value to the community but actually comport ourselves so that that greater value is realized.

Encouraging Initiative in the Engineering Student

Discussion and author's closure of a paper by C. L. Dawes published in the June issue, p. 910–4, and presented for oral discussion at the education session of the summer convention, Hot Springs, Va., June 26, 1934. (Discussions of the group of papers of which this was a part are given under the group heading on an earlier page.)

H. W. Bibber: While most of us who teach electrical engineering recognize the desirability of taking steps to develop initiative in students, we have difficulty sometimes in visualizing new ways in which this can be

accomplished, so binding are the effects of our established routines. We often feel that no way other than that which we now use would work. When those who have tried new schemes that have proved successful report on them as Professor Dawes has done in this paper, it provides a valuable stimulus to engineering teachers. It is to be hoped that others will follow his example. Not all schools now have the teaching staff or laboratory facilities needed to carry out his suggestions with the number of students they are handling. The time required for conferences to adequately supervise individually initiated work of students far exceeds that of the usual classroom exercises where groups number 20 or 30 students. One of the most significant inferences to be drawn from this paper, therefore, is that *the ratio of students to teaching staff must be lowered, and additional laboratory facilities made available if more initiative is to be developed in students at many of our colleges.*

R. E. Hellmund: Although I have previously stressed the necessity for developing initiative in the engineering student in various talks and discussions, Professor Dawes's paper with the plan he describes therein is such an interesting effort in this direction that some further comments seem justified.

As mentioned in the paper, the idea of developing initiative in the student was strongly emphasized in the paper on "The University of Pittsburgh-Westinghouse Graduate Program," presented by Professor Dyche and myself at the winter convention. However, there was no intention of suggesting that the development of initiative should be limited to graduate programs; on the contrary, it was pointed out in the closing discussion in particular that efforts for developing initiative should form an important part of the undergraduate program as well. In fact, there should be no doubt whatsoever as to the correctness of the broad fundamental that any engineering education should give as much emphasis to the development of habits, such as initiative, as it does to the acquisition of knowledge, and, furthermore, there should be no doubt as to the advisability of making efforts in this direction as early as possible in the program. The only questions which might be raised are those of how far such efforts can be carried at any one time without interfering too much with other objectives and which methods are the best for accomplishing the desired results. Depending upon the ability of the student during the various stages of his training to take the initiative in solving his problems, it is of course necessary at all times to strike the proper balance between the extremes of assisting him too much and of assisting him so little that he makes obviously wrong decisions or becomes discouraged in his work. This can be worked out only through experience and study of the individual cases.

It further must be determined which of the college activities can best be utilized for developing initiative. In the plan described by Professor Dawes, the planning of the student's program, certain laboratory work, and reading periods are used for this purpose—and no doubt to good advantage. As a matter of fact, the ideal teacher will use practically every course for this purpose. However, it is probably too much to expect that all teachers will stress this point, and frequently it may be overlooked entirely on account of the many other objectives, particularly that of imparting the required amount of knowledge in a limited period of time. For this reason, the selection of courses with this particular purpose in mind should prove of assistance. I personally have always felt that a certain amount of design or similar engineering work carried on during the entire course by engineering students would be very effective. (This is covered more fully in a paper on the subject, "Fundamental Principles in the Design of Electrical Engineering," read before the S.P.E.E. and published in the *Journal of Education,* April 1929, p. 819–33.) It would develop not only initiative but also the habit of doing creative work, which is so important in the engineering profession, and it would furthermore serve to exemplify the practical application to engineering work of the material given in the various science courses and thereby maintain the student's interest in these courses.

I am fully aware of the fact that many teachers are rather skeptical of the possibility of carrying on design or engineering tasks in the freshman year, and from my personal contact with quite a number of engineering students during that period I am willing to grant that it may be somewhat difficult. Nevertheless, I believe that it can be done, and done advantageously, if sufficiently simple subjects are selected and a certain amount of guidance given. I have observed that some of the science courses assign rather difficult tasks during the freshman year, such, for instance, as the writing of themes on the psychology of leadership, psychology of advertising, etc., and finding that the students with some guidance handle these subjects in a rather creditable manner, I am quite convinced that they could handle some of the simpler engineering or design problems equally well. If they were obliged to do so, it would certainly go a long way toward developing in them the habit of taking the initiative, of doing creative work, etc., and in addition would give them during the early part of their course a general idea of what engineering is all about, which I am sure would be very encouraging and stimulating throughout their course.

Although some of these latter remarks do not relate directly to the development of initiative, they illustrate how efforts along this line can be combined with other important objectives, which, of course, is desirable on account of the limited time available during the course.

C. L. Dawes: It is most gratifying to us who are attempting to adapt our methods of teaching engineering to meet better the needs of present day conditions to find such widespread interest in the subject as is evidenced by the number of teachers and practicing engineers participating in this session. A number of us have just come from the more extended educational convention (S.P.E.E.) at Cornell University and found similar intense interest there. Not only teachers but practicing engineers as well came from distant parts of the country to devote an entire week to the consideration of the current problems in engineering education. Although, naturally the subject was discussed in much greater detail there than here, the general tenor of the ideas expressed there was almost identical with those exemplified by the 3 papers presented at this session and the ensuing discussion. A number of schools have already liberalized their curricula, permitting wider choice of subjects, yet insisting that the program shall be unified and substantial. Some schools are already offering opportunity for emphasis on the economic and administrative aspect of engineering with less stress on highly analytical and research work for those students who have not high technical ability, but who do show aptitude for industrial and occupational work. This is along the general plan advocated by Mr. Morrow. I was also very much impressed there, as I am here, at the unanimity of opinion; not only as to the requirements which engineering education must now meet, but also that a number of schools were making changes with the object of meeting these requirements and many of the changes were similar to those suggested by these 3 papers.

Mr. Alger's statement that knowledge should be taught as a single subject is in accord with our own policies, as is indicated in my paper where it is stated that we give the degree for the satisfactory completion of a coördinated program of study. Also, in the electrical engineering department and in other departments, we emphasize the close correlation among the laws of electricity, hydraulics, heat flow, and mechanics. In fact we demonstrate electrical oscillations with mechanical models, and many mechanical problems are solved by equivalent electrical circuits. It is not easy, however, to persuade the mathematics department to teach mathematics as shorthand for describing physical realities. Usually the department also must adapt its courses to other students who have interests other than engineering and science, so that the plan usually is not practicable. However, it is my experience that students actually come to know their mathematics only after they have used it extensively in the problems of engineering and science. The engineering teacher may well do as Mr. Alger suggests, and many of us, I know, attempt to follow his suggestion.

In reference to Mr. George's discussion, the economics of engineering education is a paradoxical one. The majority of students have difficulty in meeting expenses and on the other hand, in my own institution as in most others, the tuition fee pays for only from 40 to 50 per cent of the cost of educating the student, and this cost does not include any overhead charges on buildings and equipment. Also, a large proportion of the students do not pay the full tuition but receive scholarships and other aid. As is well known, educational institutions are not extravagantly operated but actually the reverse is true. Economies that are sometimes to the detriment of the purposes of the school are frequently necessary, and certainly the teachers are not overpaid. The college and university of today can offer so much of educational value that it is really the fault of the student if he does not obtain his money's worth.

However, the economic problem of the student is a serious one and is not easy of solution. Many students of ability find it necessary to restrict their educational opportunities because of lack of funds. My own institution is attempting in part to meet the problem by awarding to a limited number of students of demonstrated ability a sufficient amount each year to meet all their educational expenses throughout the 4-year course. In addition to scholarships, loans and other aids are available to other students. A number of fellowships with stipends more than sufficient to meet living expenses are awarded to outstanding graduate students so that they can continue their studies. Also, we have increased the number of half-time assistantships so that engineering students can continue their studies after graduation, and still be earning something over actual living expenses. However, even with all these aids, there is a large number of deserving students who have insufficient funds, and as Mr. George intimates, this is a real problem.

His statement that adding another year or 2 to the present 4-year course is in the wrong direction is contrary to the opinions of many of us engineering teachers and also of many practicing engineers. The many recent developments in science and engineering and the complexity of our present day social system, which is emphasized by Professor Sorensen, necessitate a longer period than 4 years for adequate training to meet these conditions. Attempting to train students within a 4-year period has led to the many criticisms of engineering education that we so frequently hear.

Experience has shown that the plan which Mr. George advocates of a student leaving for a year or 2 to earn money for expenses does not work out well in the majority of cases. The students find it difficult to give up a paying position to resume studying again, even though it may be to their future advantage; some become married. With the usual salary which such men receive, it is difficult to save a sufficient amount over living expenses to pay for a year or 2 more at college. Also, when the continuity of study is interrupted, it is not easy to resume again after such a long period. There are many opportunities for those who wish only 2 or 3 years training without qualifying for a professional engineer. In many schools it is possible to select a group of courses which are suited to such needs. There are, however, many excellent technical institutes which offer just this type of technical training.

No one regrets more than we engineering teachers the conditions which Mr. George deplores of the young engineering graduate having difficulty in finding a position or of obtaining a salary which is at all commensurate with his engineering training. Present day economic conditions are undoubtedly in a large measure responsible for this condition and let us hope that the situation, therefore, is only temporary. There is no doubt that even in normal times, in the beginning, numbers of young engineering graduates were underpaid, but in the past those who have shown outstanding ability have as a rule been able to push up and obtain some measure of success. Professor Sorensen's enumeration of the many qualifications which are expected of the engineering graduate are in accord with the experience of many of us. Furthermore, if the graduate is in any way found deficient in any of these numerous qualifications, his engineering training has been inadequate and the methods of engineering teaching accordingly should be improved. I cannot, however, agree with his statement that the program which I describe is almost wholly prescriptive, like that at the California Institute of Technology. The entire paper emphasizes the opposite, that is, our program is entirely elective.

In answer to Professor Timbie's query as to the manner of the selection of the titles in the bibliography, these were not selected by me, but are given as submitted by the respective authors. To my mind, these references have focused attention on our present day engineering education problems as no other writings have done. With all due respect to Plato and Aristotle, it is really asking too much of these 2 ancient Greek philosophers, who have been dead some 2,200 years, to solve the many current problems of this complex machine age.

As is stated by Professor Bibber, with our plan it may require more time on the part of the instructing staff for individual conferences. However, there are compensating factors which tend to offset this. For example, the reading period at the end of each term relieves the staff of 3 weeks classroom time although some preparation for the reading period is necessary. The project method of conducting laboratory work compresses the time in the laboratory into a very few sessions and hence reduces considerably the time of laboratory supervision. Moreover, as the students become accustomed to depending on themselves, the time that they require for consultation becomes less. Before seeking advice, they of themselves have developed their plans almost completely and need advice only on some minor factors. However, as Professor Bibber states, in teaching it is an advantage when the ratio of students to instructing staff is low.

We all welcome the views of Mr. Hellmund, a practicing engineer, who not only comes in contact with large numbers of our engineering graduates but who also is instrumental in having developed an educational plan. As he states, it is necessary to strike the proper balance between assisting the engineering student too much and too little. We urge our students to come to us for assistance after they have exhausted a reasonable amount of time in the solution of a problem. It is desirable to do this for the usual student has considerable pride and does not like to admit that he cannot extricate himself from the difficulty.

The suggestion that a certain amount of design be carried on throughout the course is one well worth our consideration. Most of us do give, from time to time, some relatively short problems of a design nature. If a comprehensive design problem could be coördinated with the other subjects in the curriculum, I have no doubt that it would be well worth while and would also develop initiative and perspective in the student.

In conclusion, I feel that we electrical engineering teachers and the electrical profession as a whole have benefited mutually by the friendly interchange of the many ideas which have been expressed at this session.

Industry Demands and Engineering Education

Discussion and author's closure of a paper by L. W. W. Morrow published in the April 1934 issue, p. 518–22, and presented for oral discussion at the education session of the summer convention, Hot Springs, Va., June 26, 1934. (Discussions of the group of papers of which this was a part are given under the group heading on an earlier page.)

C. D. Backus: This paper presents a careful analysis of the subject covered, particularly of underlying conditions, and should leave no room for discussion that a remedy is necessary. There is, however, a strong probability that there will arise doubts regarding the proposed remedy in the minds of many who take a deep interest both in broad educational lines and also those which affect the engineer, not only as an engineer but as a human element in our social fabric.

In the first place, the educational requirements presented solely by industry are not alone to be considered in any final solution of the problem. The fitness of the man having a strictly engineering education for the management of industry is one question; the fitness of those who have managed, or will manage, our industries, to perform that function is quite a different subject.

Now, whence comes the assurance that a training based on proposed "course No. 1" will produce a better qualified manager for industry, when looked at from a social point of view, than those who have functioned in that capacity, whether their education be based on engineering fundamentals or on strictly non-engineering curricula, or none at all? Recent developments clearly show that plenty of our industrial managers, from the point of view of their own industries, had sufficient qualifications for the immediate purpose. Yet industry could not keep going under such management.

Where does one look for an explanation for this condition of affairs? It seems that 2 fundamental requirements have to a large extent been overlooked.

First, the engineer, and more particularly the research worker, acquires a habit of forming conclusions based only on observed facts. This is true even though as an intermediate step he formulated and used a hypothesis. Such a general course leads to sound reasoning and if followed in practice in business management and social and political affairs, it cannot fail to be helpful, in the opinion of many, in developing a saner industrial organization from the social aspect. Mr. Morrow does not overlook this feature but appears not to stress it enough. This scientific method as a desirable aspect of educational development is already receiving attention from leaders of our educational institutions and elsewhere, as especially pointed out by Secretary of Agriculture Wallace ("The Social Advantages and Disadvantages of the Engineering-Scientific Approach to Civili-

zation." *Science*, v. 79, Jan. 5, 1934). It is a reasonable expectation that pursuance of such methods will tend to minimize those results occurring because some one or some group of citizens, or even some coterie of stockholders, wishes them, or because they can be effected through mere forensic persuasion, or for similar reasons characterized in general by the fact that either the fundamentals were insufficiently ascertained or that the reasoning applied thereto was faulty, or both.

Second, the other fundamental qualification relates to the humanistic side. This subject is a large one and deserves more extensive treatment than can be given in these comments. A mere outline calls to attention that the concept of the individual's conduct toward or behavior relationship to all others jointly, that is, to the social state, should be comparable to the relationship between individuals themselves. With a low standard for the latter relationship it would be natural to consider that that of the former would be still lower. Now, it is a matter of common observation that there is much room for improvement in the relationship between individuals, in the proper development of which forces such as home training, religious training (whether regarded favorably or indifferently), and ethical or other cultural agencies no longer exert the required influence in this direction. The very complexities themselves of modern life may be partly responsible for the inadequacy of such building-up forces. However this may be, and in spite of the disclaimer that attempts made by those who would improve our economic conditions do not envision an improvement in human nature, it still remains rather obvious that society will not improve much even on its economic side so long as human nature remains static or declines in its assessable value.

Now the question arises, will society as a whole find its engineers, when confronted with these conditions, any better trained for industrial management after pursuing the courses suggested by Mr. Morrow than have been our recent industrial managers, who have been merely developed, as it were, or were more or less specially trained, but without engineering training? Recent investigations have shown plenty of instances of mismanagement in connection with control banks, holding companies, and the like (to cite one field merely for illustration) where there could be no gainsaying that the mismanagers had sufficient ability or that they knew their business. They knew their economics also, from the practical viewpoint. One sometimes wonders whether such individuals, in case they had not already had any special education in political economy, would have been improved upon from a social point of view if they had had such education. Let the economists make the answer. It seems almost certain that little or no social improvement is to be expected merely by adding to an abridged engineering education further training along the lines indicated in the suggested course, unless real and visible stress is laid on those lines of effort which will have for their effect to improve man's understanding of what his attitude shall be toward other men individually and collectively. One concrete objective, for example, might be inculcation of those ideas underlying coöperative efforts. While broad cultural education has been advocated and possessed by many leading engineers, it does not appear that either such a qualification in itself, or its prevalency, has been sufficient to produce perceptible results.

It is believed that many of our real universities already present curricula of the scope indicated by the proposed "course No. 1," also curricula which could be adapted to include deficiencies pointed out herein. It is true that much of the work as given in those curricula may not be presented in a manner to meet the object contemplated by "course No. 1." This, however, is a matter of suitable educational direction as is also the supervision of selection of that combination of subject courses adapted to meet the prospective needs of the individual student. Such a selection is fairly presupposed since existing managerial functionings obviously are different and would require different trainings.

Finally, an interesting question arises: What sort of a capacity status as citizens, or as leaders in their own expert line, will those engineers have who have been educated according to "course No. 2?"

H. W. Bibber: Those of us who are engineering teachers should, it seems to me, feel very grateful to Mr. Morrow for the very definite conclusion which he presents at the end of his paper. Others less articulate than Mr. Morrow may have felt the demands of the situation we face at present but few have set them forth as clearly. Dean Doherty of Yale expressed a somewhat similar view at the S.P.E.E. convention at Ithaca, N. Y., June 21.

Mr. Morrow seems to feel that a realignment of organization in existing institutions would have to be made before the results he describes in his conclusion could be achieved. I wonder if this would be necessary in most schools. Rather limited experience and observation on my part tends to make me feel that in many institutions it would not be necessary to create new departments or a new college. The possibility of achieving the results which Mr. Morrow describes hinges on: (1) the use of the "honors" plan and (2) the revision of the usual electrical or other engineering curricula along lines that have been rather widely discussed recently, and mentioned in part in this paper. I refer to the inclusion of more electives and the requirement of more nontechnical subjects in the course, with the accompanying omission of specialized courses. May this paper help speed the day of liberalization of engineering curricula!

The general concept I have of the modern plan which takes care of the students Mr. Morrow would have follow his course No. 1 is that an engineering course would be built up around a core of required fundamental physical science, mathematics, and social science, with basic technical courses in whatever the description of the course implies, mechanical, civil, or electrical. There would be a considerable portion of the whole curriculum free for electives and there would be options in advanced technical courses, none of which would be of the type which Mr. Morrow speaks of as "specialized." "Honors courses," such as those which have been operating with apparent success at the Massachusetts Institute of Technology and other places, rather than a special curriculum would form the means of taking care of Mr. Morrow's course No. 2 group, the future professional engineers.

My reason for believing that the men to staff and operate mechanized industry can best be obtained from the regular engineering courses of the improved type I have described is that all responsible work in the operation of modern industry consists of problem solving of one sort or another. The function of the school is, therefore, to teach the student how to solve problems, and give him some familiarity with the few principles that can truly be called fundamental. This is a trite statement but one sometimes overlooked in the heat of discussion. To teach young men how to solve problems, we can proceed most effectively if the subject matter used in the beginning is simple enough to permit the instructor's attention being concentrated on improving the students' method of attack. We should not at first burden the teacher with a discussion of the validity of assumptions, reliability of data, variations in conditions, etc., all of which are inherent in any social science material. In addition, methods of attack on physical problems by pencil and paper can be supplemented and complemented by appropriate laboratory work. Laboratory work in the social sciences requires tremendous expenditure of time. The results are often open to different interpretations and much experience is required to draw reasonable conclusions.

I may seem to imply here that a good preparation for success in a social science field is a study of applied science. I believe this to be absolutely true. Those who have great native ability succeed in the study of the social sciences in spite of the obstacles and difficulties involved in trying to learn how to attack social problems by working on the variable material presented by economic and social phenomena. Is it not easier and more logical to learn the technique of problem solving by first working with physical problems and then applying the experience thus gained to the economic or social field? Obviously the techniques of solution are not the same, but the factual approach and analytical spirit are identical. Another way of putting this whole matter is to say that to successfully solve the problems of a mechanized business a man does not have to start off his apprenticeship on the solution of business problems. He may do so, of course, but his time will be more effectively spent by beginning with the solution of engineering problems of a fundamental character, and learning the general art of problem solving first.

I quite agree with Mr. Morrow that a course to prepare men to staff and operate mechanized industry must be a welded whole and not a composite. I believe this welding process can best be carried out by the previously described broadening of existing courses in civil, mechanical, or electrical engineering. It may well be that new personnel would be required in college staffs, men with industrial experience, able to stimulate students to creative effort. With such teachers the engineering dominance which Mr. Morrow mentions would be a beneficial influence rather than a bane, if the men chosen from industry

were engineers whose experience had been as much in economic and social matters as in technical engineering. Surely there are such men.

Mr. Morrow's statement "present faculties in engineering and arts are like water and oil. They do not mix" merits comment. It was remarked by Prof. D. C. Jackson that there are such things as emulsions. Many of these are relatively stable, and extraordinarily serviceable to mankind. The value of emulsions comes precisely from the fact that the oil and water particles always retain their separate identity, but come into very intimate contact. No doubt many would agree with Mr. Morrow that some universities need an emulsifying agent. My own limited experience is that faculties in engineering and arts can mix if they are well chosen and then encouraged to do so. Putting them together and shaking them up vigorously is the logical way to accomplish the desired emulsification. It will usually work if tried, I believe. I wonder, too, how many arts college instructors in these days "teach orthodox economics." The last 4 years of depression have caused repercussions that have penetrated into even the most cloistered academic circles.

Mr. Morrow says "the ideal business course . . . is broader than engineering and requires a new perspective." If the engineering schools are preparing men for the direction and operation of mechanized industry it would seem that the definition of civil engineering as given in the charter of the Institution of Civil Engineers (London) in 1828, "the art of directing the great sources of power in nature for the use and convenience of man," is sufficiently broad and encompasses everything that Mr. Morrow mentions. With the revised type of civil or electrical engineering course there would be no lack of balance in content or lack of purpose in viewpoint, if it gave students the ability to tackle new problems effectively and familiarized them with the fundamental principles of physical and social science.

I must confess that I do not understand the first 3 pages of Mr. Morrow's paper very well. If I could grasp what Mr. Morrow had in mind I would not feel that some of his observations ought to be challenged. Mr. Morrow says that the professional engineer should do his part in social matters "largely as a citizen and not as a professional man." There will be many who will not agree with this statement. For example, the definition of "professional engineer" in the Encyclopaedia Brittanica reads in part as follows: "the engineer is under obligation to consider the sociological, economic, and spiritual effects of engineering operations and to aid his fellowmen to adjust wisely their modes of living, their industrial, governmental, and commercial procedures."

At times, as one reads the paper, it seems as if Mr. Morrow did not take cognizance of the recent tendency to employ graduates in pure science such as physics or chemistry to do more of the very highly theoretical work of research. There are, of course, engineering graduates who are doing similar work, but should they be called "engineers" any more than those engineering graduates who are now "business men?" I should like to apply the title of "engineer" rather strictly in accordance with the definition given above.

In past years the engineering graduate who later became a professional engineer picked up a good amount of his knowledge of economics and social science after graduation. Then, the physical or technical problems connected with engineering projects were so pressing that most of the attention of engineers had to be devoted to these aspects. Now, so much progress has been made in overcoming the physical difficulties and in charting the proper technical courses of action, it is but natural that the economic and social problems, heretofore somewhat neglected by the engineer but always in his domain, should be a subject for increased attention on his part professionally, and hence become matters for formal instruction in the colleges.

Another aspect possibly worth mentioning is the modern trend in education in which school is conceived to be a part of life, not an area of artificial experience. The present endeavor seems to be to make the transition from school to outside life simply another step in progress and not a radical change. Outstanding educators have long held this view I believe, but in recent years it is becoming more general. Experiments are being tried in which industrial conditions are being rather closely duplicated in the last years of the college course, in some places even to the extent of providing each student with a regular desk in the manner of engineering offices, and with stenographic service.

I cannot let the statement that "applied science or engineering is little different" [from pure science] pass unnoticed. I must refer again to the definition of engineering that I have previously quoted, and insist that engineering as widely defined over a long period of years has included a very considerable recognition of social and moral values.

Mr. Morrow and I are in most hearty agreement that the engineer has no Messianic rôle in our civilization, and I am glad to see Mr. Morrow's criticisms of the efforts that have been made to put the engineer in that false position. This does not mean however, that it is erroneous to conceive of an engineer as having some rather definite notions as to the social values of his professional work, nor that it is impossible to develop future engineers who may be more socially minded.

C. L. Dawes: In his paper Mr. Morrow specifies 2 types of engineering courses which he believes will best develop students to meet the demands of industry. One course, for the majority of students, is designed to train men as industrial executives. It will include courses in science and engineering in which these subjects are taught from the broader point of view in contrast to the highly analytical method. Also, the course as a whole will include economics, humanities, banking, and similar courses. The other course is designed particularly for a small number of selected and highly trained technical men, the object being to prepare them as specialists for technical engineering and research work.

I can heartily subscribe to these 2 objectives, for the Harvard Engineering School for some few months has had an almost identical plan under consideration. Moreover, just as Mr. Morrow's paper appeared in Electrical Engineering, Dean W. B. Donham of the graduate school of business administration at Harvard, at a meeting of the engineering faculty advised the engineering school to develop a broader engineering course, including business subjects, for the majority of students and a specialized, highly technical course for selected students. His ideas were almost identical with those given in Mr. Morrow's paper, although he had not seen it. He also stated another important fact. Of the large number of graduates of the business school, it was found that practically 300 had had engineering training, either as a formal engineering course or else had elected a sufficient number of engineering and scientific courses to give them an engineering background. The records showed that not one of these men was unemployed. Inevitably a few had lost their positions due to business changes, but they were almost immediately placed elsewhere. Hence an educator in business has come to the same conclusions as Mr. Morrow, who follows closely the teaching of engineering. Also, the statistics substantiate Mr. Morrow's statement that men with this combined type of training are in demand.

Mr. Morrow's statement that the present courses in administrative engineering do not measure up to the proposed course is in accord with our experience. For a number of years we offered a 5-year course in engineering and business administration in which the student was required to take all the specialized technical engineering courses and a number of business subjects. A limited number of men took the course and after graduation have been very successful. However, since the course apparently had unusual merits, we were surprised that it was not elected by large numbers of students. It was found, however, that after having taken the highly technical courses in which most of the problems had but a single precise solution, the students found the working of the more generalized and statistical problems and the humanitarian problems of the business world unbearable, and so lost interest. Later, many of these technically trained men entered positions in which they were obliged to meet these same types of industrial problems and were thus obliged to adapt themselves to the more general point of view. This experience confirms Mr. Morrow's statement that the engineering courses should be broader and more general than the orthodox engineering courses. Also, there is no doubt that the teachers of business and economic subjects could well modify their points of view so that they are more nearly in accord with those of the technical engineer.

Another element which is necessary to the success of such a plan is that there should be some one responsible for the plan as a whole. As Mr. Morrow states, oil and water do not mix. Unless coördinated in some way, the engineering faculty and the business and liberal arts faculty tend to remain in water-tight compartments. It is therefore necessary that some person with an engineering background and economic experience who is sympathetic to the plan be placed in charge so that adjustments and proper coördination between the different faculties can be obtained.

In the many conferences held at the recent S.P.E.E. Convention at Cornell University, the trend toward injecting economic and business subjects into the engineering curriculum was very noticeable, but many teachers seemed puzzled as to the proper procedure. Mr. Morrow's paper, coming as it does from one who has had educational experience and who is also in intimate contact with the business world, will be very helpful to such teachers in planning both the technical engineering and the administrative engineering courses.

C. Francis Harding: Such criticisms and concrete suggestions as those offered by Mr. Morrow in this paper, particularly on the part of those not immediately associated with technical education but yet familiar with the needs of industry and the shortcomings of its applicants, are greatly appreciated. I am sure that all industrial executives and technical educators will agree with Mr. Morrow in his conclusion that 2 types of engineers and of engineering training are desirable, particularly in the larger technical colleges. The problem at issue is that of the best method of classifying and training these 2 types without lowering the standards and prestige of either.

Recent studies of the problem of the possible establishment of a separate course in engineering administration at Purdue University resulted in an overwhelmingly negative vote of the engineering faculty of that institution. This vote favored the present flexible elective courses which are more readily adjustable to the needs of the individual student. As the result of such studies it is believed that the reactions of the faculty and certainly that of the writer to the following forceful statements quoted from the paper are as indicated in the comments following each quotation:

"Social sciences are not formulistic or calculable for the reason that they deal with human actions and emotions. At best they permit only the use of a statistical analysis and at worst they deal with only the social and moral averages of a mob of irrational human beings.

"But the engineer, the scientist, and the educator are called upon to apply their scientific methods of analysis and their finite solutions to the *social sciences;* to apply the cool-headed objectiveness whereby they are accustomed to reach quantitative conclusions, and yet they must retain the intelligent emotion that is necessary to motivate all human action." (p. 519)

To this we heartily agree and beg to submit that *engineering training*, plus such sociological electives as are necessary and applicable to establish the proper contact with the future problems "on location," is the proper solution of such preparation.

"The foregoing analysis indicates that the present demands from industry reduce to the possibilities of training 2 types of men: (1) a large number of men with a broad training that includes some fundamental engineering and science to fill the functional positions of a large part of industry; and (2) a small but very highly trained group of technical men who can be developed into technical specialists. . . . Yet in very few instances have the schools faced these 2 demands honestly in order to satisfy them or refuse them." (p. 521)

The latter sentence we deny at Purdue University unless we be classified among the "very few instances." We recognize both the demands and the indicated proportions of our students available for each group but we submit that individual student analysis and adaptation of sociological and economic electives are preferable to the opening of a necessarily "snap course" into which some of group No. 2 might be tempted to enter to their ultimate sorrow. Better more rigorous training for *several* future executives than superficial training for *one* potential research worker and specialist.

"Why not make a new course that incorporates the best elements of both the engineering and arts courses to prepare the large majority of college students for business life and relegate both of the older courses to more highly specialized types of education? . . . It is evident that the present courses in administrative or industrial engineering do not measure up to the requirements and possibilities of the proposed course, although they attempt to do this in some degree. These courses are unsatisfactory because present facilities in engineering and arts are like water and oil. They do not mix. In some instances the economics department dominates and in others the engineering department keeps control." (p. 521)

Again we submit that the new course is not necessary, at least in our situation. The engineering schools at Purdue University are in the vast majority and there are no colleges of arts, law, and medicine. The non-engineering and service departments are dealing primarily with engineering students and naturally assume the engineering method of attack.

"The course must be a welded whole and not a composite of courses already given in 2 departments. It must have a content, a method, an administration, and an identity of its own to be successful. It should be a separate college in the typical university organization." (p. 522)

This we believe to be unnecessary at our institution for reasons stated above. The course for *each individual student* should be a "welded whole" but such does not necessarily imply a separate curriculum and college for all.

"An essential part of this conception of a technical course is a careful selection of the students and the instructors. They must be high in quality although relatively few in number and their capacities must be measured by technical yardsticks."

To this we heartily subscribe. In fact it is recognized as an endorsement of our *individual student selection* and elective course recommendation adopted for both types of students. The technical yardstick is applied to instructors in other than engineering departments as well.

E. J. Rutan: This paper is of considerable interest at this time. I would like to draw attention to a portion of the paper which has a particular significance. Page 520, beginning with the paragraph "Occupational records of engineering graduates . . ." down to the section beginning "The Day of the Specialist Is Here" should be carefully considered.

As judged from the comments made by many educators, they express a willingness to give general business courses as part of a new engineering course, or they may already be giving such instruction under the head of "industrial engineering" or "administrative engineering." I would like to focus attention on the preparedness of industry to absorb men with this type of training in the regular way in which they have in the past handled men for technical positions. You will note that the author says those men in non-engineering work, who represent 60 to 70 per cent of the engineering graduates, apparently arrive there in a hit or miss fashion.

We are all acquainted with the program that exists in the larger companies for assimilating engineering graduates. This program, however, was built up over a period of years until it reached the stage where its functioning was well known to the various educators and was apparently satisfactory to the men employed. It is thought that it will be necessary to develop a similar program for men going into these so-called administrative or directive positions. The task will present more difficulties than that for the strictly technical men and it is well to mention some at this time.

In order to place men in directive or supervisory positions, it is necessary that they have considerable knowledge of the business. Provision must be made for obtaining this training. The qualifications for occupying supervisory positions are much more diversified than those for strictly technical work. These qualities can be determined only after careful observation and trial. The placing of men in supervisory positions supposes that they are more suitable than men in the ranks. This idea, I do not believe, will be readily accepted by most of the men in the ranks.

When technical graduates are employed for engineering work, most of the other employees are ready to consider that the engineering field requires a specialized training which the graduate has, and do not look upon him as a competitor. When the engineering graduate with the general training attempts to enter supervisory fields where men in the ranks feel they also are competitors for the position, difficulty may be expected. It is not anticipated that they will be ready to agree that the engineering graduate has those qualities which make him peculiarly fitted for the position instead of themselves. In order, therefore, to adapt the technical men to the positions which, we hope, they will be able to fill in better fashion, it will be necessary to give attention to suitable methods of introducing them into the organization and directing them through channels so that they may arrive in positions of responsibility without causing unrest among those who work for them.

This problem was brought up in my work several years ago but, due to business conditions, was dropped at that time. It has recently come up again in connection with a study of the men occupying supervisory positions. In some instructions by my superior regarding the study of this problem, a statement was made which can well be repeated as a warning that this program cannot be organized as quickly as some may think. The statement was along the following lines:

In introducing these engineering men into supervisory positions, you must be careful not to set up an aristocracy.

R. E. Hellmund: For the last few years I have followed with interest the many discussions on engineering education, stressing the necessity for broadening the curriculum to include non-technical subjects to a greater extent. A broad education for an engineer seems, of course, very desirable and one therefore hesitates to contradict statements to that effect. However, I have never been convinced that it is desirable to delete from the curriculum some of the

subjects absolutely essential for engineering and now generally included in the 4-year courses, nor am I very much in favor of extending engineering courses beyond the 4-year period. In general, I rather feel that as far as preparation for actual engineering work is concerned, the 4-year courses should primarily attempt to turn out efficient engineers and devote just enough time to a number of non-technical subjects to arouse an interest in such subjects. Where post-graduate work is possible for an engineer while he is practicing his profession, the inclusion of some of these broadening subjects is undoubtedly of advantage. In view of this opinion on my part, I rather welcome Mr. Morrow's viewpoint, which frankly recognizes the practical limitations and suggests one type of course which is primarily devoted to subjects needed for engineering work.

In analyzing this whole question, we realize that much of the discussion relating to the broadening of an engineering education has sprung from conditions created by the depression. Since our unemployment problems have been caused to a certain extent by engineering activities directed toward labor saving, the feeling has developed that it is the responsibility of the engineer to broaden his activities and to direct his attention toward solving this problem which he is accused of having created. As an engineer engaged purely in engineering work, I have therefore often wondered what I and my associates similarly engaged could possibly do about it. Assuming, for the sake of argument, that the education of these engineers was broad enough to include all such subjects as enter into the depression and unemployment problems, I was forced to conclude that such knowledge would be of little value to these engineers or anybody else unless they were willing to step out of the engineering profession and take up activities along entirely different lines. As far as the engineer who is engaged in regular engineering work in industry is concerned, his opportunities for exerting his efforts in broad activities are distinctly limited. He can, of course, take part in general educational work and he can, individually or through his activities in the various professional societies, assist in disseminating correct information regarding engineering and industry. In connection with the unemployment situation, he can support any movements for adjusting working hours to meet the demands of the times, appreciating that a gradual shortening of working hours will be a more or less natural development, as it has been in the past.

In addition to these incidental activities, he has, however, one major possibility to contribute toward the correction of the situation, and that is by creating through his engineering activities greater demands for industrial products. This he can do by devising entirely new products which will be useful in some way or other, by making existing products better and more useful, or by making such products available to a greater number of people through further reduction in cost. In other words, his principal opportunity to contribute effectually toward the problems of the day is through more and better engineering, or, in other words, in more efficient work in his own particular line.

All of this simply indicates that courses intended to prepare students for engineering work should have as their primary aim the production of efficient engineers. This in turn means that they should include thorough training in such subjects as physics, chemistry, mathematics, etc. Since the engineer's work should be directed principally toward the production of something of use to the human race and toward satisfying human needs and desires, the curriculum should preferably include some well selected course in psychology and, obviously industrial and engineering economics (not national or international economics and finance) should receive attention. Last, but not least, engineering courses should be directed toward developing interest in and ability to carry out typical engineering tasks.

Regarding the other type of course advocated by Mr. Morrow, there is no doubt that it will fill a real need. The designation "industrial engineering" seems to be quite appropriate for this course, but as pointed out in the paper, present courses going by this name do not entirely cover what the author has in mind. This is possibly due to the fact that the industrial courses are comparatively new in most schools, but I believe that their further development along the lines suggested in the paper is not only desirable but entirely feasible.

In general, after looking over typical curriculums of engineering colleges, I believe that with few exceptions the subjects listed are entirely as they should be. On the other hand, there frequently seems to be room for improvement in the way of a more careful selection of the material to be presented in such courses, and a method of presentation more suitable for engineering students. There also seems to be a need for better correlation of the various courses and for the choice of a better time for their presentation. The present quite common practice of turning the engineering student over to the college of arts and science for the greater part of the first 2 years of his course and of not giving him during that period even an inkling of what engineering is does not appeal to me. As a matter of fact, I consider it hardly fair to a student who has embarked in training for engineering to keep him practically in the dark as to what engineering work is really like for almost 2 years of his training, and up to a time when it is usually of great disadvantage for him to make a change to some other line of work.

Mr. Morrow's suggestion to weld the pure science courses and the engineering courses into one college has a great deal of merit. However, even if it is not possible to bring about this major change, it seems essential that the engineering schools should govern and take part to a greater extent in the training of the student during the first 2 years, which in turn may of course make it necessary to extend some of the science course into the third and fourth years. With the present arrangements, the engineering schools seem to have but little influence upon the work given to the students in other departments, and if an English teacher sees fit to teach an engineering student old English instead of training him in the best use of the English language in modern industry, there seems to be little that the engineering school can do about it. The study of old English is most interesting, but in my opinion it has no place in an already very crowded course for engineers.

Unfortunately the time available does not permit comment on many of the ideas given in Mr. Morrow's paper, most of which I can, however, heartily endorse.

L. W. W. Morrow: It is stimulating to hear so many constructive comments or suggestions for improving engineering education. We all agree that what is desired is an educated man and that education only starts in the colleges. It is also apparent that the majority agrees that engineering education is valuable because of its method and technique in addition to the contents of the courses. The trained engineer is an analyst and he is taught to seek facts in order to arrive at logical conclusions.

But the form of university organization and the types of courses to be taught are debated. Engineers in the field are well agreed that 4 years is sufficient time for the majority of students to spend in college. The addition of another year or 2 in order either to broaden or to narrow the college training is not economic and not practical. Therefore the general discussion reduces to plans for 4 years in college.

In my opinion the introduction of any great amount of cultural or economic course content in an engineering course designed to train men for professional engineering is inadvisable and impracticable—it weakens the professional training and is insufficient to give any appreciable element of broad training. In other words, with elevated technical standards for engineers, the 4 years in college should be devoted to technical training just as is the case with students in law and medicine. The infiltration of economic and cultural courses or the use of the optional method weakens rather than strengthens the present courses which are already below standard in technical content. I prefer the approach that modernizes and elevates the present technical courses.

For the large mass of young men who expect to enter upon business careers, as pointed out in several discussions, there is a possibility of developing an organization and a course that will be an improvement upon the present engineering courses or those in business and commerce. Such a course would use the engineering method and technique in instruction. It would not be a "snap" course. It can be developed to give a training in technology, economics and business more adequate and more rounded than those now available.

I agree with the comments that all educated men should have social consciousness and the broadest possible knowledge. But we are speaking of what is possible and practicable in the undergraduate period of life and in the present educational organizations. The present engineering schools are doing excellent work and their graduates are finding their places in all types of industry activities. The suggestions therefore that were made were general and not formulistic or rigid and were presented to the end that present trends in industry and in education might develop along logical lines to a culmination that appears to be an improvement upon present practices.

News

Of Institute and Related Activities

Salt Lake Convention Upholds Coast Reputation

OPENING on Labor Day, Monday, September 3, 1934, the 22d Pacific Coast convention of the Institute held forth during the week at the Hotel Utah in Salt Lake City. Enthusiasm at the technical sessions and during the entertainment features remained high throughout the week.

B. C. J. Wheatlake, chairman of the general convention committee, called the opening session to order at 2 o'clock Monday afternoon, with more than 140 members and guests present. Paul F. Keyser, president of the Salt Lake City chamber of commerce, in his welcoming address cited the long electrical history of the state of Utah, dating back to the historic initiation of high voltage transmission by the Telluride Power Company in Provo Canyon. Acting on behalf of President J. Allen Johnson, who was unable to attend, Vice President R. W. Sorensen of Pasadena, Calif., responded for the Institute, reëmphasizing some of the principal aims and objectives of the Institute, and urging engineers in general and electrical engineers in particular to stop "waiting for something to happen," and to proceed with the development of projects that will be of service to mankind. Turning his remarks to the younger engineers, Professor Sorensen urged that they should extend their activities into the fields where the products of engineering skill are used, and not limit their activities to the fields of development and production; he urged that activities and influence be extended through direct participation in the social and economic problems of community and state. By way of offsetting the tendency for the younger engineers to feel that there is no place for them, Professor Sorensen emphasized for one thing the "replacement market" throughout the industries in whose services electrical engineers are now indispensable, as well as the new industrial and other activities that now offer the enterprising electrical engineer an opportunity to reëstablish himself.

Attendance

A fitting testimonal to the unremitting efforts of the various convention committees was the fact that the total registration was 232 persons, and the fact that the attendance at the various technical sessions averaged above 100 and went as high as 140-odd. The territory considered as contributory to the Pacific Coast convention includes Districts 8 and 9, and the western portion of District 10; there were members and delegates present at Salt Lake, City from 13 out of the 14 student Branches in this territory, and from most of the 7 Sections. National officers of the Institute present included Vice Presidents R. B. Bonney of Denver, Colo., R. W. Sorensen of Pasadena, Calif., and F. O. McMillan of Corvallis, Ore.; past vice presidents of the Institute present included: Dean H. V. Carpenter, Pullman, Wash., A. W. Copley, San Francisco, Calif., and C. R. Higson, Salt Lake City, Utah. The attendance is analyzed in the accompanying tabulation.

Analysis of Attendance at 1934 Pacific Coast Convention

Classification	Location: Salt Lake City	Dist. No. 9*	Dist. No. 8	Misc.	Totals
Members	26	15	33	25	99
Men Guests	10	7	4	7	28
Women Guests	27	13	16	11	67
Students	10	14	14	—	38
Totals	73	49	67	43	232

* District No. 9 outside of Salt Lake City.

Technical Sessions

The 5 technical sessions were held Monday afternoon, and Tuesday, Wednesday, Thursday, and Friday mornings, featuring the 25 papers listed in the convention program as published on p. 1128–29 of ELECTRICAL ENGINEERING for July 1934. As to subject matter and general interest, the sessions were devoted respectively to communication, management and protective devices, lightning, transmission, and a selected group of special research papers. Presiding over these meetings, respectively, were George T. Royden, of San Francisco, Calif., A. LeRoy Taylor, of Salt Lake City, Utah, Vice President F. O. McMillan of Corvallis, Ore., national transmission and distribution committee chairman D. M. Simmons, of New York, N. Y., and Past Vice President A. W. Copley of San Francisco.

Taking advantage of the unified publication plan, the committee in charge of the technical program for the Salt Lake City convention was able to schedule for discussion at the 5 sessions 25 papers instead of the previous limit of 14 or 16. Consequently the scope of interest was noticeably broadened and the discussion was particularly active and widely participated in, both by those present and by absentees through the medium of written discussion. Subject to the review and recommendation of the technical program committee, this discussion will be published in an early issue of ELECTRICAL ENGINEERING.

Student Activities

In addition to the general technical program, 2 entire afternoon sessions were devoted to the presentation of 12 student papers. The Tuesday afternoon session was presided over by Robert Ingebretsen of Stanford University, and the second student session was presided over by Don Pugsley, of the University of Utah, Salt Lake City. The student papers presented were as follows:

THE PERIODICITY ANALYMATOGRAPH, S. Hansen and G. K. Barger, University of Washington.

A NEW ILLUMINOMETER, Warren Patton, California Institute of Technology.

TRANSMISSION OF SOUND ON A BEAM OF LIGHT, W. H. Flanze, James W. Gilmer, and J. M. Kennedy, University of Montana.

SAN FRANCISCO-OAKLAND BAY BRIDGE CONSTRUCTION RADIOTELEPHONE SYSTEM, D. Reginald Tibbetts, University of Idaho.

AN AUDIO OSCILLATOR PIANOTRON, D. J. Ward, University of Idaho.

AUTOMATIC SYNCHRONIZATION, M. G. Lewis, University of Santa Clara.

ELECTRICAL MEASUREMENT OF WATER VELOCITY, J. K. Moore, Oregon State College.

THE GENERATING ELECTROSTATIC VOLTMETER, E. A. Schuchard, University of Washington.

A STUDY OF THE HIGH-TENSION MAGNETO IGNITION SYSTEM WITH SPECIAL REFERENCE TO THE SOURCE AND ELIMINATION OF RADIO INTERFERENCE, W. B. Smith, University of British Columbia.

FLASHOVER TESTS IN OIL, Ray Kidd, California Institute of Technology.

CORONA ATTENUATION WITH ARTIFICIAL LIGHTNING WAVES OF SHORT DURATION, P. DeK. Dykes, Stanford University.

ECONOMIC COMPARISON OF INCANDESCENT LAMPS, Max Llewellyn and Edward Eardley, University of Utah.

In addition to the student technical sessions already mentioned, the Enrolled Students and their counselors participated in a luncheon meeting Tuesday, September 4, and in the annual student conference that was held in part as a luncheon meeting after the close of the general session Friday afternoon. The latter meeting was presided over by Vice President Sorensen, who opened the session with a brief address emphasizing the importance of student activities in the further development of the Institute, and urging full coöperation of all concerned.

Of the 14 Student Branches in Districts 8, 9, and the western part of 10, all were represented by student chairmen or vice chairmen, and all but one were represented

Membership—

Mr. Institute Member:

By this time you have received a letter asking you to help your Section membership committee by sending in the name of one person who you feel should be invited to join the Institute. Your willingness to do this in the past has helped us to record a considerable increase in membership applications. If you have not yet replied to the letter, will you not do so promptly?

Very truly yours,

Chairman National Membership Committee

also by the student counselor. Branch counselors present included: A. L. Albert, Ore. State Col., E. F. Peterson, Univ. of Santa Clara, W. A. Hillebrand, Univ. of Calif., R. H. Hull, Univ. of Idaho, G. R. Shuck, Univ. of Wash., S. G. Palmer, Univ. of Nev., F. C. Lindvall, Calif. Inst. of Tech., O. E. Osburn, State Col. of Wash., and J. A. Thaler, Montana State Col.

The Branch chairmen present included: J. C. Garrett, State Col. of Wash., John V. Kelly, Univ. of Ariz., M. G. Lewis, Univ. of Santa Clara, T. M. Libby, Univ. of Wash., T. B. Lyman, Univ. of Calif., Donald Odell, Univ. of Nev., A. E. Opdenweyer, Ore. State Col., O. E. Osburn, State Col. of Wash., E. F. Peterson, Univ. of Santa Clara, E. E. Simmons, Calif. Inst. of Tech., and G. L. Stancliff, Jr., Univ. of Southern Calif.

One of the subjects most widely discussed at the student conference was the relative advisability of planning Student Branch programs on the basis of having outside speakers in the persons of practicing engineers, as against building such programs on the basis of entirely student presentations. Some favored one, and some favored the other, but the final general consensus of opinion seemed to be that a proper balancing of the 2 in the light of the peculiar conditions that may affect any one Branch produces the best over-all results.

At a group conference of the counselor-delegates for District No. 8, Prof. F. C. Lindvall, student counselor at California Institute of Technology, Pasadena, was chosen to act as District student counselor chairman for the ensuing administration year. A similar conference of the counselor-delegates from District No. 9 resulted in the choice of Prof. O. E. Osburn, student counselor at State College of Washington, Pullman, to act as District student counselor chairman for the ensuing administration year.

Entertainment Program

The entertainment program, judging by the general comments of those present, was pleasant in its variety, and satisfying in its quantity and quality. The program was formally initiated at the reception held Monday evening at the Hotel Utah, followed by dancing, although the enterprising local women's entertainment committee gathered all the women guests in attendance Monday afternoon and took them on a delightful automobile tour to points of scenic interest in the vicinity of Salt Lake, followed by tea at a popular rendevous. Other features presented especially for the entertainment of women guests in attendance at the convention were the bridge luncheon and the approaching and putting contest on the golf course, both of which were held Thursday afternoon at the Salt Lake Country Club. First prize in contract bridge went to Mrs. R. W. Sorensen of Pasadena, Calif.; for auction bridge to Mrs. W. B. Clark of Salt Lake City. In the putting contest, first honors went to Mrs. H. N. Raymond of Boise, Idaho; second honors to Miss Helen Rockwell of Los Angeles, Calif. Honors for the best approach shot were divided between Mrs. A. H. Brolly of San Francisco, and Mrs. D. K. Brake, Butte, Mont.

Most of those attending the convention took the opportunity of listening to the Tuesday noon organ recital at the Mormon Tabernacle, and later in the afternoon participated in a general excursion to Saltair where they disported themselves in the 28-per cent salt solution of the Great Salt Lake. The lake is at its lowest point in history, and the water has receded so far that it requires the services of a half-mile tramway to carry the bathers from the end of the pier out to the present actual water's edge.

The principal technical inspection trip, and excursion combined, was out to the mine and mills of the Utah Copper Company in Bingham Canyon, where many enjoyed themselves profitably Wednesday afternoon. Other parties were conducted to other points of mining and industrial interest, according to their choice.

An informal dance held at the Old Mill Club, in the vicinity of Salt Lake Wednesday evening, drew a large crowd, and the capstone of the convention entertainment program was represented by the convention banquet held Friday evening at the Salt Lake Country Club where some 150 or more of those attending the convention gathered for the final celebration and the awarding of golf prizes.

Acting at the request of J. A. Kahn who presided at the head table, Vice President Sorensen awarded the 1933 technical paper prizes for District No. 8: best Student Branch paper, to John H. Genzenhuber, of the University of Southern California, Los Angeles; best initial paper to A. H. Albrecht, Standard Oil Company of California, La Habra; best paper for the year, Lloyd F. Hunt and Alex A. Kroneberg, of Los Angeles. Final decisions on similar awards for District No. 9 had not been reached, and announcement consequently was deferred.

Golf

The annual golf tournament drew an entry list of 29 golfers and aspirants who had looked at the display of prizes, including the prized and coveted Fisken Cup. The affair was held on the beautiful and challenging course of the Salt Lake Country Club, Thursday, September 6.

The Fisken Cup, named for John B. Fisken (A'03) of Spokane, Wash., was won by H. W. Flye of San Francisco, Calif. For low net honors, Mr. Flye, M. M. Keneally of Mansfield, Ohio, and H. M. Ferguson of Salt Lake City, Utah, were tied; Mr. Ferguson won the toss to break the tie. The best fundamental golfer of the day proved to be E. W. Rockwell of Los Angeles, whose gross 86 topped the records.

Future AIEE Meetings

Winter Convention,
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 24–26, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory (Date to be determined)

Among the special awards were the following: for high gross score, Past Vice President H. V. Carpenter, of Pullman, Wash.; for the longest drive on No. 3 hole, E. W. Rockwell; for the best third shot on No. 18, Chester Coon of Oakland, Calif.; fattest golfer, M. M. Keneally; thinnest golfer, E. H. Martindale, Cleveland, Ohio; for the best No. 2 tee shot, S. L. Case of Oakland, Calif.; for blind bogey J. A. Kahn of Salt Lake City, and H. W. Flye and H. M. Ferguson were tied.

Committees

The general convention committee in charge of this most successful convention was: B. C. J. Wheatlake, *chairman;* R. W.

Sorensen, A. C. Kelm, W. R. Barrett, A. LeRoy Taylor, J. A. Kahn, C. A. Malinowski, L. E. Brown, C. R. Higson, W. L. Winter, J. A. Hale, J. Hugh Hamilton, Mrs. L. B. Fuller, F. O. McMillan, H. T. Plumb, L. B. Fuller, A. H. Hull, A. P. Hill, J. A. Thaler, V. B. Wilfley, W. C. Smith, G. L. Hoard, W. M. Allen, and L. R. Stacey. The chairmen of the various subcommittees working with the general convention committee were as follows:

Entertainment—W. L. Winter, *chairman;* P. P. Ashworth, A. W. Copley, R. J. Corfield, H. H. Krueger, and F. E. Young, Jr.

Finance—J. A. Kahn, *chairman;* W. R. Barrett and A. C. Kelm.

Golf—J. A. Hale, *chairman;* W. L. Winter and J. Hugh Hamilton.

Hotels and Registration—L. E. Brown, *chairman;* H. B. Waters and C. A. Wolfrom.

Publicity—L. B. Fuller, *chairman;* M. L. Cummings, Elwood Bachman, and Harvey Hancock.

Reception—C. R. Higson, *chairman;* S. D. Packard, A. C. Kelm, and H. B. Waters.

Technical Program—A. LeRoy Taylor, *chairman;* C. R. Higson, H. T. Plumb, Fred Lundberg, and John A. McDonald.

Student Activities—J. Hugh Hamilton, *chairman;* J. Hugo Johnson, Nathan C. Clark, and F. C. Lindvall.

Transportation—C. A. Malinowski, *chairman;* D. L. Brundige, Frank E. Young, Jr., Sigurd A. Bloomquist, and Fred Lundberg.

Ladies' Entertainment—Mrs. L. B. Fuller, *chairman;* Mrs. J. A. Hale, Mrs. C. R. Higson, Mrs. B. C. J. Wheatlake, Mrs. J. A. Kahn, Mrs. H. T. Plumb, Mrs. W. L. Winter, and Mrs. C. A. Wolfrom.

Nomination of A.I.E.E. Officers for 1935 Election; Members Invited to Submit Suggestions by Nov. 15

FOR THE nomination of national officers to be voted upon in the spring of 1935, the A.I.E.E. national nominating committee will meet between November 15 and December 15, 1934. To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee, all such suggestions must be received by the secretary of the committee at Institute headquarters, New York, N. Y., not later than November 15, 1934. In accordance with the provisions of the constitution and by-laws, quoted herewith, actions relative to the organization of the national nominating committee now are under way.

Constitution

28. There shall be constituted each year a national nominating committee consisting of one representative of each geographical district, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical districts; all to be selected when and as provided in the by-laws. The national secretary of the Institute shall be the secretary of the national nominating committee, without voting power.

29. The executive committee of each geographical district shall act as a nominating committee of the candidate for election as vice president of that district, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The national nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The national nominating committee shall name on or before December 15 of each year, one or more candidates for president, national treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice presidents as have been named by the nominating committees of the respective geographical districts, if received by the national nominating committee when and as provided in the by-laws; otherwise the national nominating committee shall nominate one or more candidates for vice president(s) from the district(s) concerned.

By-Laws

SEC. 22. During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district that by November 1 of that year the executive committee of each district must select a member of that district to serve as a member of the national nominating committee and shall, by November 1, notify the secretary of the national nominating committee of the name of the member selected.

During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district in which there is or will be during the year a vacancy in the office of vice president, that by November 15 of that year a nomination for a vice president from that district, made by the district executive committee, must be in the hands of the secretary of the national nominating committee.

Between October 1 and November 15 of each year, the board of directors shall choose 5 of its members to serve on the national nominating committee and shall notify the secretary of that committee of the names so selected, and shall also notify the 5 members selected.

The secretary of the national nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than December 15. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the national nominating committee must be received by the secretary of the committee by November 15. The nominations as made by the national nominating committee shall be published in the January issue of ELECTRICAL ENGINEERING, or otherwise mailed to the Institute membership during the month of January.

(*Signed*) H. H. HENLINE,
National Secretary

October 1, 1934.

A.S.M.E. Annual Meeting. The technical program for the 55th annual meeting of The American Society of Mechanical Engineers, to be held in New York, N. Y., Dec. 3–7, 1934, is well under way. Among the sessions being planned are the following: domestic heating; industrial power, and central station power; heat transfer; vibration, materials, stress analysis, and bearing analysis; aeronautics; machine design,

A Group at the Institute's Recent Pacific Coast Convention

This group, showing about half of those registered at the Institute's 22nd Pacific Coast convention, held this year at Salt Lake City, Utah, September 3–7, was photographed on the Temple Grounds Tuesday noon, September 4

Repairing a Conductor Carrying 38,000 Volts

THE above reproduction of a photograph received from H. L. Talbot (A'14, M'25) Bolivian Power Company, Ltd., Oruro, Bolivia, South America, shows men performing work which is believed to be quite original and which may be of interest to engineers in other countries. According to information received from Mr. Talbot, their single circuit steel tower transmission line of 4/0 aluminum conductor steel reinforced cable has developed serious conductor breakage due to crystallization of the aluminum strands at the suspension ears. The remedy for this recommended by the manufacturer of the cable was the installation of tapered aluminum armour rods twisted around the main conductors at each ear. The line is 3 phase, 38,100 volts, 50 cycles, and cannot be shut down for repairs. As no hot-stick equipment has as yet been developed for doing this kind of work, it must be performed by hand with actual personal contact. The work is being carried out successfully by the special method developed in the field for its performance. Mr. Talbot states that if any member of the Institute is interested in knowing how this work is being done he would be very pleased to give him all details. With the exception of the foreman in charge of the work, they do not have a single man on the job who has had previous line or even electrical experience, as the war between Bolivia and Paraguay has drafted all physically fit men in the working ages.

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metal cutting, broaching, and welding; management; and prevention of occupational disease disability. Papers will also be presented on education, training in the industries, fan design, and research on steam, mechanical springs, boiler feedwater, and fluid meters.

Refrigerating Machinery Association Meeting. The annual meeting of the Refrigerating Machinery Association will be held October 22, 1934, at the Stevens Hotel, Chicago, Ill. At this meeting, officers will be elected and activities will be planned for the coming year. The past year has been especially productive in the coöperative exchange of technical information, standardization of equipment, and the promotion of a high standard of trade practices.

Radio Engineers to Meet at Rochester. The program for the Rochester fall meeting of the Institute of Radio Engineers, to be held at the Sagamore Hotel, Rochester, N. Y., November 12–14, 1934, has been announced. Among the subjects to be discussed are iron core tuning systems, high fidelity reproducers with acoustical labyrinths, automatic reactance control systems, applications of ultra-high frequencies, diode coupling considerations, centimeter waves, cathode wave tubes in receiver distortion measurements, converter tubes at high frequency, input losses in vacuum tubes at high frequencies, detector distortion, inductive interference, and new equipment. Brief discussions on the desirability of the reduction of radio interference from several different viewpoints also will be presented.

Standards

Membership Increase Reported by A.S.A.

According to an announcement made by Dr. P. G. Agnew (A'12, M'19) secretary of the American Standards Association, that association has reached an all-time peak in membership, in spite of present business conditions. The A.S.A. now has 42 member-bodies and associate members, and 1,233 company members. Since January 1934, 9 associations have become member-bodies or associate members. During this period, 11 other companies have joined the association, and 4 corporations have voluntarily increased their dues.

The A.S.A., national clearing house for standards and safety codes, was formed in 1918 by 5 technical societies which felt the need of developing inter-industry standards out of their own technical standards. More than 260 codes have been developed by the association and nearly 200 are under development or are being devised. More than 3,000 engineers, scientists, and industrialists, representing manufacturers, technical societies, consumers, and government departments, serve on its numerous committees.

Engineering Foundation

Second Volume of Arch Dam Report

The extensive 10-year field and laboratory research on problems of constructing and designing arch dams, which was carried on by The Engineering Foundation, was completed in 1933. (See Elec. Engg. for July 1933, p. 511–2.) Volume II of the report on the investigation of arch dams is now being printed, and completes the reports on this work. This volume, of 550 pages, approximately twice as many as either Volume I or Volume III, records the study of models of dams, and of materials therefor, and special studies of portland cement concrete. A copy will be supplied to each contributor to the fund for the research. Members of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers may purchase copies from The Engineering Foundation at $3 each; other persons at $4 each.

American Engineering Council

Prominent Engineers Named on Federal Aviation Commission

A practical approach to the aviation problem has been made by the appointment of 2 outstanding aeronautical engineers on the new 5-member board which will develop national policies for civilian and military aviation, according to a statement made recently by F. M. Feiker, executive secretary of American Engineering Council. The President recently named, as members of the federal aviation commission, Edward P. Warner, recognized as a leading authority on heavier-than-air craft, and Jerome C. Hunsaker, who is of similar prestige in the lighter-than-air field.

Mr. Warner, formerly a professor of aeronautical engineering in Massachusetts Institute of Technology, served as assistant secretary of the Navy for aeronautics from 1926 to 1929, and is now editor of the magazine, *Aviation*. Mr. Hunsaker also instructed in aeronautical engineering at M.I.T., where he has returned to head the mechanical engineering department. He was a commander in the Navy in charge of aircraft design. He is an officer of Goodyear-Zeppelin, International Zeppelin, and other companies.

Both men are members of American Engineering Council's committee on aeronautics of which Mr. Warner is chairman. Through this committee, Council is seeking to bring to bear the advice of organized engineers upon problems of the aviation industry along lines followed for the past decade.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Engineering Service

To the Editor:

President J. A. Johnson in his message in the August 1934 issue of ELECTRICAL ENGINEERING, p. 1142, said that he expected to do considerable thinking about the Institute's position in the "New Deal" and invited comment. He mentioned 9 definite movements which somewhat confuse the situation.

I have had to do some deep thinking myself as my friends know that I left Westinghouse last March and opened a consulting office in the Gulf Building in Pittsburgh. I believe that any effort the engineer makes for his own benefit must be based upon the fundamentals of service that is of direct value to some going organization. The "trade union" idea of combination to increase salaries and benefits is not the way to start. The engineer must command respect and a fair return for his services but first he must do things that will justify this respect and remuneration. Much more can be accomplished by coöperation through organization than by individual effort. Few men have that "all round" ability and experience necessary to handle the complicated situations in our present social order. Each of us has definite abilities and experiences which can be combined into a strong group which is mutually supporting and capable of wonderful accomplishments. Many commercial groups have commercial limitations that restrict engineering activities to definite channels. The A.I.E.E. is one of the few national groups that is free from such limitations where engineers can work for the common good which is the best way to advance our profession.

We need this kind of coöperative effort now more than ever. When it is necessary for individuals to reduce their society activities it is better to concentrate on our national society because of its broader possibilities. Individual members directly benefit largely in proportion to the efforts they put into their society. The profession as a whole is helped through the combined effort of the membership. During a depression like this one it may be necessary for us to do as many business enterprises have done, namely, to concentrate our efforts.

A lack of business has given many groups an opportunity to do some careful thinking and investigation, with the results that new things and new results will be available when business comes back and the time is ripe to release them. Engineers and business executives should be alive to this situation. The publications of the national societies are full of new things that should stimulate the engineering imagination. Many of these ideas and deductions are still in the theoretical stage and require the application of business judgment to make them commercial. Business men will not disclose their plans before they are ready to enter the market but the A.I.E.E. is an open forum for the exchange of engineering information; it is a good place to go for ideas.

Very truly yours,

H. D. JAMES (A'98, F'12)
(Consulting Engineer, Gulf Building, Pittsburgh, Pa.)

Graphical Solution of Delta-Star Resistance Transformations

To the Editor:

In solving networks it is frequently desirable to replace a delta combination of resistances or reactances by an equivalent wye which will give the same terminal voltage and current conditions. This well-known relationship is (see Fig. 1):

$$a = \frac{BC}{A+B+C} \text{ and } aA = bB = cC$$

As a mathematical recreation it is interesting to prove that these wye values can be found by the following graphical construction (see Fig. 2):

1. Construct a triangle with sides proportional to the delta resistances.
2. Draw the angle bisectors.
3. From their intersection draw lines parallel to the sides. These lengths are proportional to the desired wye resistances.

PROOF (see Fig. 3):

1. Draw lines parallel to the sides through the intersection of the angle bisectors.
2. From the similar triangles cxa and ABC

$$\frac{c}{a} = \frac{A}{C} \text{ and } \frac{x}{a} = \frac{B}{C}$$

3. $B - c - a = x$
4. (Substituting) $B - \frac{A}{C} \cdot a - a = \frac{B}{C} \cdot a$
5. $CB = Aa + Ca + Ba$
6. $a = \frac{BC}{A+B+C}$
7. The other relationships are found by using the appropriate triangles.

EXAMPLE

The example shown by the figures has the following proportionate values:

$A = 10$	$a = 3.2$
$B = 8$	$b = 4.0$
$C = 12$	$c = 2.6$

Very truly yours,

WILLIAM W. EDSON (M'25)

(Electrical Engineer, Construction Dept., Edison Electric Illuminating Co. of Boston, Mass.)

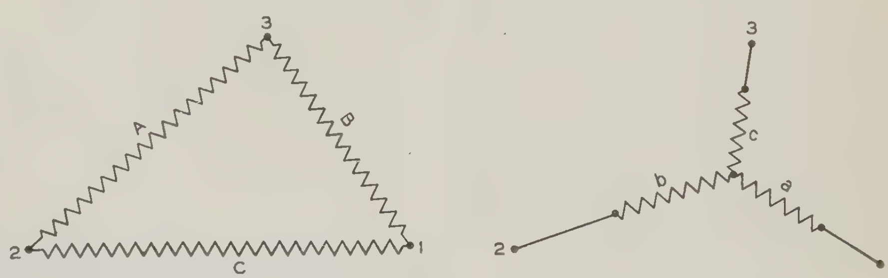


Fig. 1

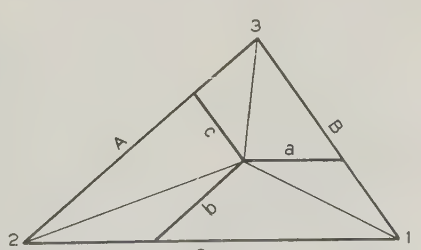


Fig. 2

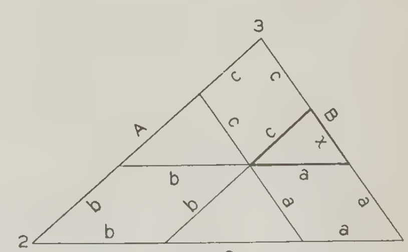


Fig. 3

Personal Items

C. O. Bickelhaupt (M'22, F'28) assistant vice president, American Telephone and Telegraph Company, New York, N. Y., has been appointed chairman of the Institute's publication committee for 1934–35. He was born at Roscoe, S. D., in 1888, and received the degrees of B.S., in 1911, and E.E., in 1914, from the University of Wisconsin. During several summers preceding graduation in 1911, he was employed by the Dakota Central Telephone Company. In the latter year he entered the American Telephone and Telegraph Company as an engineering assistant, becoming general commercial problems engineer in 1920, toll traffic engineer in 1922, and later in that year commercial engineer. From 1925 to 1930 he was vice president, director, and member of the executive committee of the Southern Bell Telephone Company, and during 1925–26 also held these offices in the Cumberland Telephone and Telegraph Company. Since 1930 he has been an assistant vice president of the American Telephone and Telegraph Company and a director of the Bell Telephone Securities Company. He has been a vice president and a director of the Institute, and has served on a number of committees. He has been reappointed as chairman of the committee on economic status of the engineer, and in addition is a member of the following committees: award of Institute prizes; constitution and by-laws; coördination of Institute activities; and technical program. Mr. Bickelhaupt also is the Institute's representative on the American Engineering Council and the Engineers' Council for Professional Development. He is a member of the New York Electrical Society and of the American Engineering Council, of which he is a vice president and committee member and chairman.

H. P. Sleeper (A'22, M'30) Public Service Electric and Gas Company, Newark, N. J., has been appointed chairman of the Institute's protective devices committee for the year 1934–35. Mr. Sleeper was born at Bangor, Me., and graduated in 1915 from the University of Maine with the degree of B.S. in E.E. Until 1917 he worked as assistant foreman in the electrical block signal department of the Maine Central Railroad at Brunswick. He then entered the advanced student course of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa. In 1917 he entered the U.S. army, and after being promoted to the rank of captain, was wounded in action in France, November 1918. In 1919 he returned to the employ of the Westinghouse company as a design engineer in the instrument and relay department. In 1923 he entered the employ of the Duquesne Light Company, Pittsburgh, Pa., as protection engineer and remained there until 1925 when he took a similar position with the Public Service Company. Since 1929 Mr. Sleeper has been in the general office under the transmission and substation engineer in charge of the operation of substations and switching stations. He has developed many new schemes of relay protection, and has been especially interested in perfecting operating procedures for high voltage electrical equipment, with particular reference to personnel safety. Mr. Sleeper holds 12 patents. He has presented several papers before the Institute, and has written various articles in technical magazines. He was the editor-in-chief of the N.E.L.A. relay handbook supplement published in 1931. He has served on various technical committees of the Institute, and has been a member of the protective devices committee since 1926.

J. Allen Johnson (A'07, F'27, and president) chief electrical engineer, Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., has been appointed chairman of the executive committee of the Institute for 1934–35. He is also a member of the following: board of directors; Edison medal committee; and Charles A. Coffin fellowship and research fund committee. He is also representative on the American Engineering Council. A biographical sketch of Mr. Johnson appears on p. 230 of the January 1934 issue of Electrical Engineering in connection with his nomination for the presidency, and a photograph on p. 1038 of the July 1934 issue.

L. W. W. Morrow (A'13, F'25) editor, *Electrical World*, New York, N. Y., has been appointed chairman of the committee on coordination of Institute activities for 1934–35. He was born at Hammond, W. Va., August 7, 1888, and was educated at public schools in Fairmont, W. Va., Fort Worth, Texas, and Amarillo, Texas, followed by preparatory schooling at Marshall College, Huntington, W. Va. In 1907 he entered Cornell University and graduated in 1911 with the degree of M.E., remaining for 2 years as an instructor. He then went to Norman, Okla., as assistant professor of electrical engineering at the University of Oklahoma, where he later became an associate professor and acting director. In 1918 he went to Yale University, New Haven, Conn., where he was an assistant professor of electrical engineering until 1922, when he became affiliated with the McGraw-Hill Publishing Company, Inc., of New York, on the editorial staff of *Electrical World*, of which he became editor in 1928. Mr. Morrow is a director of the Institute and has served on many committees. He is now a member of the board of examiners, and of the following committees: finance; legislation affecting the engineering profession; applications to marine work; membership; production and application of light; and technical program. He also is Institute representative on the Engineers' Council for Professional Development.

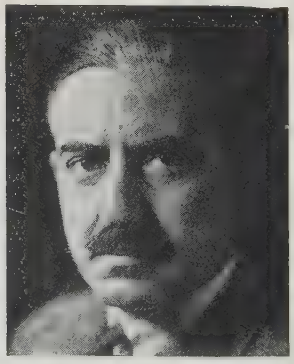
R. H. Tapscott (A'18, F'29, and vice president) vice president, New York Edison Company, New York, N. Y., has been appointed chairman of the finance committee of the Institute for 1934–35. He is also a member of the following committees: board of directors; coördination of Institute activities; executive; and headquarters. A biographical sketch of Mr. Tapscott appears on p. 231 of the January 1934 issue of Electrical Engineering in connection with his nomination for a vice presidency, and a photograph on p. 1038 of the July 1934 issue.

H. M. Hobart (A'94, F'12, and member for life) consulting engineer, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's committee on electric welding for 1934–35. He was born at Boston, Mass., in 1868, and graduated from the electrical engineering course at Massachusetts Institute of Technology in 1889. He then entered the employ of the former Thomson-Houston Company at Lynn, Mass., transferring to Schenectady, N. Y., with the formation of the General Electric Company, but later returning to Lynn. From 1900 to 1911 he was in Europe, principally in London, England, where he practiced consulting engineering for 8 years. During this time he was a lecturer at English educational institutions. Upon his return to this country he became associated with the General Electric Company as a consulting engineer. He has been particularly interested in electric welding, and was a member of the welding committee of the Emergency Fleet Corporation. Mr. Hobart has served on a number of Institute committees, and is now

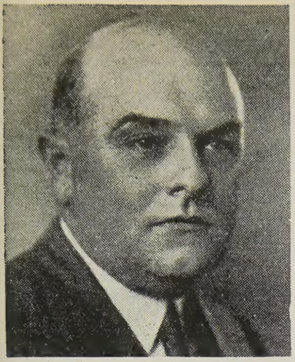
H. P. SLEEPER

C. O. BICKELHAUPT

Kaiden-Kazanjian Studios

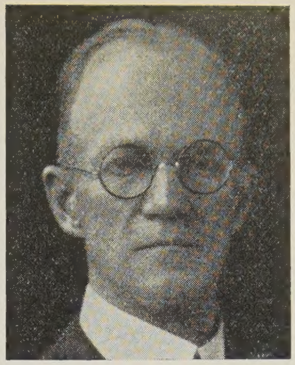


L. W. W. MORROW



E. B. MEYER

V. M. MONTSINGER



H. M. HOBART

a member of the research committee, and also is Institute representative on the American Bureau of Welding. He is a member of the Institution of Civil Engineers, Institution of Mechanical Engineers, and Institution of Electrical Engineers, all of Great Britain; and of The American Society of Mechanical Engineers and American Welding Society, and a fellow of the American Association for the Advancement of Science.

E. B. MEYER (A'05, F'27) vice president United Engineers and Constructors, Inc., Newark, N. J., has been appointed chairman of the Institute's committee on constitution and by-laws for 1934–35. He was born in Newark, and in 1903 graduated from the Pratt Institute, Brooklyn, N. Y. He entered the employ of the Public Service Corporation of New Jersey and remained with that organization until he was appointed chief engineer of the Public Service Production Company in 1922. He became a vice president of that company in 1929, and of United Engineers and Constructors, Inc., in 1930 when the 2 companies merged. Mr. Meyer has been very active in Institute affairs and has served on many committees. He was a director 1927–31 and a vice president 1932–34. He is now a member of the following committees: coördination of Institute activities; Edison medal; publication; and transfers; and is representative on the Engineering Societies monograph committee.

V. M. MONTSINGER (A'14, F'29) research engineer, General Electric Company, Pittsfield, Mass., has been appointed chairman of the Institute's electrical machinery committee for 1934–35. He was born at High Point, N. C., and graduated from the University of North Carolina in 1909 with the degree of B.S. He entered the transformer department of the General Electric Company in January of the following year. From that time until 1922 he devoted most of his time to the study and development of practical thermal laws relating to the heating of transformers and to improved methods of cooling transformers. Since 1922 his time has been devoted mostly to the study and development of simple and workable dielectric laws for insulations, and means for insulating transformers to withstand high voltage stresses, particularly of the transient type. He has been a member of the Institute's electrical machinery committee since 1926, and he has been reappointed as a member of the standards committee, on which he has served since 1928, where he has been active in keeping the Institute Transformer Standards up to date in reflecting the latest practice. He has written numerous technical articles for engineering journals.

W. T. RYAN (A'07, M'12) professor, department of electrical engineering, University of Minnesota, Minneapolis, was elected a member of the council of the Society for the Promotion of Engineering Education at the annual meeting in June at Ithaca, N. Y. Professor Ryan has served on 2 Institute committees, production and application of light, 1928–30, and education, 1929–33, and was a vice president, 1928–30.

F. W. SMITH (A'05, M'12) president, New York Edison Company, United Electric Light and Power Company, and Brush Electric Illuminating Company, has been elected a member of the board of trustees of the Northwestern Mutual Life Insurance Company, Milwaukee, Wis. He has participated in committee work of the company, and was a pioneer in advocating the investment of insurance company funds in public utility bonds.

H. C. DEAN (A'12, F'30) general superintendent, New York and Queens Electric Light and Power Company, Flushing, N. Y., has been elected a vice president of the company. He has been identified with the utility since 1916, becoming general superintendent in 1917. He has served on the Institute's power transmission and distribution committee, 1929–32, and the board of examiners, 1933–34.

L. M. KLAUBER (A'11, F'23) vice president in charge of operation, San Diego Consolidated Gas and Electric Company, San Diego, Calif., is a director of the Pacific Coast Electric Association. Mr. Klauber was a member of the Institute's power transmission and distribution committee, 1921–25, and its representative on the American Association for the Advancement of Science council, 1931.

T. S. TAYLOR (M'21) director, T. Smith Taylor Laboratories, Caldwell, N. J., has been appointed head of the physics department at Washington and Jefferson College, Washington, Pa., but will continue his consulting service. Doctor Taylor was a member of the committee on research, 1928–30, and is the Institute's representative on the committee on heat transmission of the National Research Council.

C. E. MAGNUSSON (A'05, F'13, and Life Member) head of the electrical engineering department of the University of Washington, Seattle, has been named permanent chairman of the Washington State Planning Council's technical advisory committee. Dr. Magnusson was an Institute vice president 1920–21, and has served on a number of committees.

C. C. CURTIS (M'23) who recently succeeded A. M. Chitty (M'22) as district manager, Puget Sound Power and Light Company, Olympia, Wash., has been transferred to Stone and Webster, Inc., as personnel director for that organization. He has been connected with Stone and Webster enterprises since 1907.

SIDNEY HOSMER (A'97, F'12, and member for life) vice president and general manager, Edison Electric Illuminating Company of Boston, Mass., was honored by his associates on July 11, 1934, the 40th anniversary of his association with this utility. Mr. Hosmer became a vice president in 1926 and general manager in 1932.

E. F. SCATTERGOOD (A'08, F'13) chief electrical engineer and general manager, bureau of power and light, Los Angeles, Calif., has been named the first national chairman of the newly organized National Municipal Utilities Association. He was a member of the power stations committee of the Institute 1914–17.

A. S. MOODY (A'09) northwestern manager, General Electric Company, Portland Ore., has been elected a member at large of the executive committee of the Northwest Electric Light and Power Association. He was Institute representative on the U.S. national committee of the International Electrotechnical Commission, 1919–22.

GEORGE SUTHERLAND (A'20, F'27) formerly assistant general superintendent, New York and Queens Electric Light and Power Company, Flushing, N. Y., is now general superintendent. He was a member of the board of examiners 1929–30, and of the standards committee 1927–34.

GERARD SWOPE (A'99, F'22) president, General Electric Company, New York, N. Y., has been named to membership on the advisory committee of the American Standards Association. He has been on the Iwadare Foundation committee of the Institute, 1931–34.

J. E. ROYER (A'15) vice president and general manager, Washington Water Power Company, Spokane, has been elected a member-at-large of the executive committee of the Northwest Electric Light and Power Association.

J. H. McGraw (A'01 and member for life) chairman of the board, McGraw-Hill Publishing Company, New York, N. Y., has been named to membership on the advisory committee of the American Standards Association.

H. R. Stewart (A'26) formerly general engineer, Westinghouse Electric and Manufacturing Company, Boston, Mass., has become protection engineer for the New England Power Engineering and Service Corporation, Boston.

W. S. Gifford (A'16) president, American Telephone and Telegraph Company, New York, N. Y., has been named to membership on the advisory committee of the American Standards Association.

L. A. Grettum (A'24) Eastern Oregon Light and Power Company, Baker, Ore., has been elected state vice president for Oregon of the Northwest Electric Light and Power Association.

M. S. Oldacre (A'13) has been appointed equipment planning engineer in the equipment section of the Commonwealth Edison Company, Chicago, Ill.

L. I. Anderson (A'25) has been appointed equipment standardization engineer in the equipment section of the Commonwealth Edison Co., Chicago, Ill.

Obituary

Walter Wood (A'04) partner, R. D. Wood and Company, Philadelphia, Pa., died April 20, 1934. He was born at Philadelphia on Dec. 6, 1849, and received the degree of A.B. from Haverford College in 1867 and from Harvard University in 1868. In that year he entered R. D. Wood and Company, an organization which was founded in 1803. Mr. Wood was treasurer of the Millville Gas Works and president of the Florence Iron Works. He was also a director of the Burlington (N. J.) City Loan and Trust Company, and a trustee of Haverford College. He was a member of The American Society of Mechanical Engineers, the American Institute of Mining and Metallurgical Engineers, the American Society for Testing Materials, and the American Waterworks Association. His club membership included: Union League, Manufacturers', Art, University, and City, all of Philadelphia; Machinery, Engineers', University, Harvard, and City of New York.

Paul Bernard Selden (A'08, M'13) industrial tests and layouts, Springfield, Mass., died on December 12, 1933. He was born at Hallsport, N. Y., January 21, 1878. After graduating from the Bliss Electrical School in 1900 he worked for short periods of time for the Union Telephone and Telegraph Company, Bradford, Pa., and the New York Edison Company, New York. In 1904 he went to Springfield as superintendent in the meter department of the United Electric Light Company. He became chief electrician in 1908, with charge of all additions to electrical station equipment. In 1917 he engaged in consulting engineering, and 4 years later became electrical engineer for McClintock and Craig, Springfield, which position he held until recently.

Richard Little Wilson (A'22) wire chief, Braden Copper Company, Rancagua, Chile, was accidentally killed there some 2 years ago, according to word just received at Institute headquarters. He was born at sea aboard the British sailing vessel "Primrose Hill" on July 13, 1889. His education was received at schools in Altrincham and Bowden, in Cheshire, England. In 1905 he joined the Wardle Engineering Company in Manchester as an electrician, and for short periods subsequently was employed by engineering firms in Edinburgh, Scotland, and Belfast, Ireland. In 1914 he became telephone foreman for the Braden company in Rancangua, and assumed the position of wire chief in 1921.

Edward Marc Duvòisin (A'23) lightning arrester engineering department, General Electric Company, Pittsfield, Mass., died on July 6, 1934, after a short illness. He was born at Grandson, Switzerland, May 21, 1894. He graduated from the University of Lausanne in 1917, and from then until 1922 was engaged in work at Geneva and Lausanne, Switzerland. In that year he came to the United States and entered the test department of the General Electric Company in Schenectady, N. Y., and after 2 years there he was transferred to the lightning arrester department in Pittsfield.

Foster D. Keese (A'20) instructor and textbook writer, International Correspondence Schools, Scranton, Pa., died on Aug. 14, 1934, from gangrene. He was born at Rome, N. Y., Aug. 7, 1889. Upon completion of the electrical engineering course at Syracuse University in 1910 he entered the test course of the General Electric Company at Schenectady, N. Y., and remained with that company until 1914, when he became an instructor for the correspondence school. He was engaged in this work until his death with the exception of a year in the radio branch of the U.S. signal corps at the time of the war.

Mitchell Aaron Kreindler (A'32) maintenance man, Union Gas and Electric Company, Cincinnati, Ohio, died in a New York hospital on August 10, 1934, and was buried in Cincinnati. He was apparently recovering from an illness but suffered a relapse. He was born at New York on August 28, 1908. He was a graduate of the electrical engineering course at the University of Cincinnati, class of 1931, and had been employed as maintenance man since January 1929.

Membership

Recommended for Transfer

The board of examiners, at its meeting held September 19, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Member

Coulthard, Wm. B., asst. prof. of E.E., Univ. of British Columbia, Vancouver.
DuBois, N. W., supt. of distribution, Dominion Elec. Pwr. Ltd., Estevan, Sask.
Evans, Haywood W., asst. system relay engr., Va. Elec. & Pwr. Co., Richmond.
Geiger, James M., E.E., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Gray, John L., electrolysis engr., Louisville Gas & Elec. Co., Louisville, Ky.
Hodges, Ralph C., E.E., Titanium Pigment Co., Spotswood, N. J.
Holden, Omar W., Jr., E.E., Bureau of Pwr. & Lt., Los Angeles, Calif.
Johnson, Kenneth H., relay engr., Niagara, Lockport & Ontario Pwr. Co., Jamestown, N. Y.
Kroneberg, Alex A., tech. asst. to operating engr., So. Calif. Edison Co. Ltd., Los Angeles.
Levy, Mortimer N., 40 West 72 St., N. Y. City.
Milbyer, Joseph H., gen. supt., Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Presley, Evans E., supt. of lines, Tonawanda Pwr. Co., No. Tonawanda, N. Y.
Sawyer, Mark A., protection engr., So. Calif. Tel. Co., Los Angeles.
Schlaikjer, Hugo C., asst. engr., Bklyn. Edison Co. Inc., Bklyn., N. Y.
Smith, Farquhar W., asst. gen. engr., Va. Elec. & Pwr. Co., Richmond, Va.
Smith, Harry B., elec. pwr. trans. engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Tennant, George E., engg. asst., The Syracuse Ltg. Co. Inc., Syracuse, N. Y.
Wilkinson, B. J., dist. commercial mgr. and pwr. engr., Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Wilson, Dean, supervising draftsman, Pacific Gas & Elec. Co., San Francisco, Calif.
Wright, Sherwin H., elec. engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.

20 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Oct. 31, 1934, or Dec. 31, 1934, if the applicant resides outside of the United States or Canada.

Adashko, J. G., Ford Instr. Co., L. I. City, N. Y.
Alfred, G. E., Gibbs & Hill, N. Y. City.
Allen, A. S., Tonawanda Pwr. Co., N. Tonawanda, N. Y.
Babcock, G. S., Drake Hotel, Chicago, Ill.
Bailey, W. F., Stevens Inst. of Tech., Hoboken, N. J.
Bobier, F. C., Gen. Elec. Co., Schenectady, N. Y.
Bonacio, T. J., 11 Main St., Cold Spring, N. Y.
Castle, D. McC., Calif. Portland Cement Co., Colton.
Curry, A. R. (Member), Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.
Egan, F. D. (Member), Bethlehem Steel Co., Lackawanna, N. Y.
Freudenberger, W. J. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Fuller, D. C. (Member), Bd. of Pub. Util., Jamestown, N. Y.
Greene, H. G. (Member), Bethlehem Steel Co., Lackawanna, N. Y.
Harris, C. H., Va. Elec. & Pwr. Co., Richmond.
Hawke, R. S., Louisville Gas & Elec. Co., Ky.
Heffner C., Okla. Gas & Elec. Co., Oklahoma City.
Heinz, C. A., 1925 Cecil Ave., Baltimore, Md.
Heston, W. S. (Member), Gen. Elec. Co., Buffalo, N. Y.
Isbister, E. J., 1126 84th St., Bklyn., N. Y.
Jaenecke, L. E., Tonawanda Pwr. Co., N. Tonawanda, N. Y.
Joehnck, K. M., Gen. Elec. Co., Schenectady, N. Y.
Jolliffe, C. B. (Member), Federal Communications Commission, Washington, D. C.
Keller, C. L., Toledo Edison Co., Toledo, Ohio.
Leidy, H. B., Westinghouse Elec. & Mfg. Co., Wilkes-Barre, Pa.
Marvin, G. S., Central Ill. Lt. Co., Peoria.

Noble, T., Bureau of Pwr. & Lt., Los Angeles, Calif.
Ochsner, W. W., Southwestern Lt. & Pwr. Co., Lawton, Okla.
Parker, J. A. (Member), Niagara, Lockport & Ontario Pwr. Co., Jamestown, N. Y.
Plant, W. L., Tonawanda Pwr. Co., N. Tonawanda, N. Y.
Podowitz, S., 1920 Walton Ave., Bronx, N. Y. City.
Pollock, R. B., So. Calif. Edison Co., Ltd., Los Angeles.
Randall, H. L. (Member), Buffalo Gen. Elec. Co., N. Y.
Rankin, O. T., Toledo Edison Co., Toledo, Ohio.
Samuel, A. L. (Member), Bell Tel. Lab., N. Y. City.
Sieminski, E., 420 Sawyer St., New Bedford, Mass.
Smith, J., Canada Wire & Cable Co. Ltd., Regina, Sask., Can.
Stankevich, P. A., Bklyn. Edison Co., Bklyn., N. Y.
Thompson, R. E. (Member), Trinidad Elec. Trans. Ry. & Gas Co., Trinidad, Colo.
Thornton, W. N. (Member), U. S. Navy, Navy Yard, Boston, Mass.
Towle, J. M. (Member), Buffalo Gen. Elec. Co., Buffalo, N. Y.
Turner, H. R. (Member), Bethlehem Steel Co., Lackawanna, N. Y.
Vivian, J. H., So. Calif. Edison Co., Ltd., Los Angeles.
Voelkner, G. A. (Member), C. & W. I. R. R. & Belt Ry. Co., Chicago, Ill.
Walker, E. A., Tufts Col., Medford, Mass.
Warner, J. C. (Member), R. C. A. Radiotron Co., Harrison, N. J.
Williams, D., Toledo Edison Co., Sylvania, Ohio.
Yerger, L. K. (Member), Buffalo Gen. Elec. Co., Buffalo, N. Y.

47 Domestic

Foreign

Aristarov, A. V., Research Inst. of Shipbuilding, Leningrad, U.S.S.R.
Colwell, H. P. (Member), Victorian Rys., Melbourne, Victoria, Australia.
Haase, D. A., Lago Oil & Transport Co., Ltd., Aruba, D. W. I.
Howell, W. P., San Fernando Borough Council, San Fernando, Trinidad, B.W.I.
Lamm, A. U., Allmanna Svenska Elektriska Aktiebolaget, Vesteras, Sweden.
Marfatia, R. M., Indian Inst. of Sci., Bangalore, India.
Mehta, J. J., Bombay Municipality, Municipal Workshops, Bombay, India.
Raman, P. N., Chittoor Elec. Supply Corp., Ltd., Mylapore, Madras, India.
Watkins-Ball, C. G., Metropolitan-Vickers Electrical Co. Ltd., Manchester, Eng.

9 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Adams, William C., 801 S. Lynn St., Champaign, Ill.
Babloozian, Levon M., 776 N. Cass St., Milwaukee, Wis.
Handley, Wilbur H., 4416 Loren Ave., Los Angeles, Calif.
Jordan, Henry, 7408A Christopher Colombus, Montreal, Que., Can.
Losoncy, William A., 14067 Cherrylawn Ave., Detroit, Mich.
Mexal, J. Rene, 86–03 Britton Ave., Elmhurst, L. I., N. Y.
Moellendick, K. F., L. A. Automotive Works, 1010 Towne Ave., Los Angeles, Calif.
Schultz, Carl H., 15 Cook St., Jersey City, N. J.
Simpson, Sidney, Deputy Loco. Supt., Eastern Bengal R. R., Kanchrapara, Bengal, India.
Stuntz, Hans, 106 Peck Ave., Newark, N. J.
Villegas, Lucio P., Tacoma General Hospital, Tacoma, Wash.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.

12 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

APPLIED ACOUSTICS. By H. F. Olson and F. Massa. Phila., P. Blakiston's Son & Co., 1934. 430 p., illus., 9 x 6 in., lea., $4.50. The principles of acoustical engineering and discussion of the design, construction, operation, and analysis of modern acoustical and electro-acoustical apparatus; fundamental acoustic equations, systems of sound transmission, fundamental acoustical measurements, laboratory apparatus, microphones, telephone receivers, loud speakers, architectural acoustics, noise, physiological acoustics, and miscellaneous applications of acoustics.

CIVIL ENGINEERING HANDBOOK. By L. C. Urquhart. N. Y. & Lond., McGraw-Hill Book Co., 1934. 885 p., illus., 9 x 6 in., lea., $5.00. A compact, comprehensive book to which the practicing engineer can refer when confronted with a problem outside a specialized field. Civil engineering is covered in 10 sections each by a well-known authority: surveying, railway and highway engineering; mechanics of materials, hydraulics, stresses in framed structures, steel design, concrete, foundations, sewerage and sewage disposal, water supply and purification. Much tabular matter usually incorporated in handbooks is omitted and attention is given especially to fundamental theory.

COST ACCOUNTING for CONTROL. By T. H. Sanders. 2 ed. N. Y. & Lond., McGraw-Hill Book Co., 1934. 517 p., illus., 9 x 6 in., cloth, $4.00. A revised and enlarged edition of the author's "Industrial Accounting," brought up to date and in line with the new problems introduced by government control of industry. As in the previous work, emphasis is upon the meaning of costs and their uses in management, rather than upon matters of technical procedure.

ENGINEERING DRAFTING. By W. G. Smith. N. Y. and Lond., McGraw-Hill Book Co., 1934. 236 p., illus., 9 x 6 in., cloth, $2.25. A course for the beginner which aims to develop, in addition to skill as a draftsman, independent thinking and initiative. Part 1 presents the fundamentals of the subject; part 2, its applications to machine, airplane, and pictorial drafting.

ENGINEER'S SKETCH-BOOK of MECHANICAL MOVEMENTS, Devices, Appliances, Contrivances, and Details. By T. W. Barber. 6 ed. London, E. & F. N. Spon, Ltd.; N. Y., Engineers Book Shop, 1934. 355 p., diagrs., 9 x 5 in., $4.50. Collection of mechanical movements popular with designers and mechanics for nearly 50 years. The present issue contains almost 3,000 sketches of machines and machine elements of all kinds, classified and indexed.

50 JAHRE BERLINER ELEKTRIZITÄTS-WERKE 1884–1934. ed. by C. Matschoss, E. Schulz, A. T. Gross, in Kommission with VDI-Verlag. Berlin, 1934. 247 p., illus., 12 x 8 in., cloth, 9 rm. A contribution to the history of electrical engineering, issued on the fiftieth anniversary of the founding of the Berlin Electric Works and tracing the development of the municipal electric system from then to the present day. Both economic and engineering features are described in detail. A chronological table is included, as well as a bibliography.

KINEMATICS of MACHINES. By G. L. Guillet. 3 ed. New York, John Wiley & Sons, 1934. 276 p., illus., 9 x 6 in., cloth, $3.00. In this college text the author has kept in mind the knowledge of physics and mathematics to be expected of the sophomore student, and the amount of time usually allotted to the study of kinematics. The book does not attempt to cover the field completely but gives a selection of material of decidedly practical interest. Fundamental mathematical analyses of motions in machines and useful graphical constructions pertaining to them have been given preference over purely descriptive matter.

MACHINE DRAWING. By E. F. Tozer and H. A. Rising. N. Y. and Lond., McGraw-Hill Book Co., 1934. 317 p., illus., 9 x 6 in., cloth, $3.00. A text and problems in accordance with good drafting-room practice which will bridge the gap between the fundamentals of freshman drawing and advanced treatises on machine design. The problems trace the production of a machine from the conception of the idea to its completion.

MATHEMATICAL TABLES, reprinted from Searles and Ives' Field Engineering with additions. Compiled and arranged by H. C. Ives. 2 ed. N. Y., John Wiley & Sons, 1934. 160 p., illus., 7 x 4 in., lea., $1.50. A collection of the mathematical tables most frequently wanted is presented in a volume small enough to be carried easily in the pocket. The type is clear and great care has been taken for accuracy. The new edition has been enlarged from 14 to 18 tables.

NEW BACKGROUND OF SCIENCE. By Sir James Jeans. N. Y., Macmillan Co., 1933. 301 p., illus., 8 x 5 in., cloth, $2.50. A discussion of the discoveries of Einstein, Bohr, Heisenberg, and others, and explanation of how these have led to a new philosophy. As in previous books, Sir James has kept in mind the general reader, as well as the student of physics, and the book is eminently clear and readable.

(The) KINETIC THEORY of GASES. By L. B. Loeb. 2 ed. N. Y. & Lond., McGraw-Hill Book Co., 1934, 687 p., illus., 9 x 6 in., cloth, $6.00. The aim of this work is to provide students and investigators with a book presenting the classical and more modern aspects of the kinetic theory in a form suitable for use as a college text and handy reference work. The new edition has been thoroughly revised and largely rewritten, in the light of developments since the first publication.

Great Britain. Dept. of Scientific and Indus. Res. Illum. Res. Tech. Paper No. 15. INDUSTRIAL LIGHTING, Pt. 2. LIGHTING for CRANES. Lond., His Majesty's Stationery Office, 1934. 8 p., diagrs., 10 x 6 in., paper, 3d. (Obtainable from British Library of Information, $.10.) This paper, the second of a series upon dock lighting, considers the methods of fitting lighting units to shore cranes and makes recommendations concerning the best systems.

POWER PLANT TESTING, a Manual of Testing Steam Generating Equipment, Engines, Turbines, Pumps, Refrigerating Machinery, Fans, Fuels, Lubricants, etc. By J. A. Moyer, 4 ed enl. N. Y. & Lond., McGraw-Hill Book Co., 1934. 614 pp., illus., 9 x 6 in., cloth, $5.00. This volume gives in some detail the generally approved methods of testing engines, turbines, boilers and power-plant auxiliary machinery, accompanied by descriptions of the apparatus used and the calibrations required for accurate work. This edition has been rewritten and enlarged, particularly with reference to the codes for testing approved by various engineering societies, and again represents up-to-date practice. The book is intended as a laboratory manual for students and a reference book for the engineer of tests.

PRACTICAL BUSINESS STATISTICS. By F. E. Croxton and D. J. Cowden. N. Y., Prentice-Hall, 1934. 529 p., illus., 9 x 6 in., cloth, $3.50. The collection, tabulation, graphic presentation and interpretation of statistics are here discussed in a clear manner. The treatment is concerned only with elementary statistical procedures, but includes those commonly wanted in business. The text seems well adapted for students of business methods.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Thyrite Protects Meters From Lightning.—Safe, convenient protection against failure due to lightning is provided for polyphase watthour meters by a new device, the Thyrite meter-protector, recently introduced by the General Electric Co. The device, designed to be mounted as part of the meter installation, is intended for use on relatively long and exposed secondary circuits of 650 volts or below. An installation of 500 of these new protectors has been made by the Consumers Power Co., Jackson, Mich., on a three-phase 480-volt secondary for industrial-customer service. Previously, lightning failures were numerous. However, with most of the new protectors in operation during the major part of the lightning season, failures due to normal causes have been practically eliminated on protected meters. The device consists essentially of three single-pole protectors each of which is made up of a Thyrite disk and a small series gap. The whole is contained within a steel enclosing case, 5 1/2 in. high, 4 1/8 in. wide, and 2 1/2 in. deep. Thyrite is a non-porous, inorganic, ceramic material, which General Electric has used successfully for years in the manufacture of lightning arresters.

Bakelite Laminated "Sandwiches."—Meeting a need for a product that must be "as soft as rubber and long-wearing as Bakelite Resinoid," Synthane Corp. of Oaks, Pa., is manufacturing, under Bakelite Corp. patents, a new material consisting of layers of soft rubber "sandwiched" between sheets of Bakelite Laminated. An infinite number of combinations are possible, since the layer thicknesses may be varied, as well as the number of alternating layers of rubber and laminated material. Uses suggested are gasket applications where a combination of axial resiliency with strength and rigidity is required and for vibration-absorbing machine mountings.

New Heavy Duty Blower.—The Ideal Commutator Dresser Co., Sycamore, Ill., has announced an addition to its line of portable cleaners in the Jumbo model designed for the most extreme heavy-duty dust, dirt and lint cleaning work. The new machine blows, suctions and sprays. It is powered by a full horsepower G-E motor. It may be used to blow or vacuum all dirt from motors and machinery or to clean irregular surfaces before painting. An attachment sprays paint, varnish or any liquid or powder.

New Compact Circuit Breaker Interrupts 20,000 Amperes.—The Westinghouse Electric & Mfg. Co. announces a new low voltage "De-ion" breaker, similar in general to the standard 600-ampere, 600-volt AB breaker brought out several years ago, with the major exception that the new breaker has an interrupting capacity of 20,000 amperes. The new AB-20 is totally enclosed, being mounted in the standard 600-ampere molded case. It is available in all ratings from 50 to 600 amperes, complete with standard tripping accessories and motor mechanism. To secure a heavy duty AB-20 breaker it was necessary to double the interrupting capacity of the standard AB breaker. This was accomplished by a complete redesign of the contact structure and major modifications in the "De-ion" chambers and operating mechanism. The cold cathode principle of arc extinction, which has been successfully used in the standard duty breakers, has been retained.

Additions to Square D Switch Line.—The addition of 100- and 200-ampere switches to the new Square D 50,000 line of type A switches has been announced by Switch & Panel Division, Square D Co., Detroit, Mich. The new catalog numbers are now in production. This completes the line up to and including 200-ampere switches in either standard sheet metal boxes or cast aluminum enclosures, with cast iron enclosures optional, if specified. The new 100- and 200-ampere numbers include all the features of the 30- and 60-ampere switches of this line, with some added points necessitated by the higher capacities. They are quick-make, quick-break, with interlocked covers and elevated removable bases for easier wiring. The enclosures are considerably smaller than those of the conventional type of knife switch due to the compact design of the interiors. Among other features are double-break contacts with steel spring reinforcements assuring constant pressure on the contacts for reduced heating and Square D positive pressure contacts.

Trade Literature

Insulators.—Bulletin 28 pp. Describes a comprehensive line of switch and bus type insulators. Complete specifications are included. Locke Insulator Corp., Baltimore, Md.

Transformers.—Bulletin 300, 4 pp. Describes a line of distribution transformers in which it is announced many valuable improvements have been introduced. Pennsylvania Transformer Co., 1701 Island Ave., Pittsburgh, Pa.

Electrically Operated Valves.—Bulletin 1, 2 pp. Describes the Hoppe electro-hydraulic valve designed for pressures up to 250 lb. The line pressure opens and closes this valve. Bulletin 2, 2 pp. Describes an electro-magnetic valve for remote control of oil, gas, air, and water lines. A. F. Hoppe Engineering Co., 246 S. Meridian St., Indianapolis, Ind.

Aluminum Paint.—Booklet, 64 pp. Describes the uses and applications of aluminum paint in a wide range of industries, including the electrical; profusely illustrated. Specifications as to the composition and the use of the paint on various surfaces are included. Aluminum Company of America, Gulf Bldg., Pittsburgh, Pa.

Broadcasting Equipment.—Bulletin 15A, 20 pp. Describes Western Electric speech input equipment, a self-contained unit for use with a radio transmitter situated at a distance from the studios. Bulletin 701A, 28 pp. Describes studio speech input equipment and control panel. Bulletin, 10 pp. Describes type 618A dynamic microphone and 80A amplifier. Graybar Electric Co., 420 Lexington Ave., New York.

Thyrite Lightning Arresters.—Bulletin GEA-1304C, 12 pp. Describes Thyrite form D lightning arresters, station-type, in which many new refinements have been developed. Potential stresses resulting from lightning are reduced to an extremely wide margin below the dielectric strength of the apparatus, a feature of great importance in extending the service life of apparatus. General Electric Co., Schenectady, N. Y.

Illumination.—Bulletin, 24 pp. Recommended Standards of Illumination. Comprises a new set of recommended foot-candle standards for illumination design, divided into distinct classifications depending upon the visual tasks to be considered, and offering recommended values for each and every duty common to stores, offices, factories, schools, and outdoors. General Electric Co., Inc., Nela Park, Cleveland, O.

Control and Distribution Apparatus.—Catalog 34, 64 pp. Describes the Bull Dog line of controlling and distributing apparatus for electric light and power, including safety and meter service switches, SAFtoFUSE range switches, Fusenters, lighting and metering panels, SAFtoFUSE convertible distribution panels and switchboards, circuit breaker apparatus, Trol-e-duct and electro BUStribution systems. Bull Dog Electric Products Co., Detroit, Mich.

Geared Reduction Motors.—Bulletin. Describes the "Syncrogear" motor, offering variations in speed from 2 rpm up to 10,000 rpm. The new machine is a self-contained motor with a single base, embodying a geared transmission foundationed on a heavy gear pedestal base, which supports the unusual torque strains in high torque geared reductions. The complete assembly occupies practically no more space than an ordinary electric motor. U. S. Electrical Manufacturing Co., 1510 So. Western Ave., Chicago, Ill.

Magnetic Contactors.—Bulletin 1901, 4 pp. Describes d-c magnetic contactors, 1- and 2-pole, designed for continuous duty operation, 2- or 3-wire control. They can be used as control contactors for direct current motors, for disconnect purposes in conjunction with suitable auxiliary switches, battery charging circuits and for special control panels. Bulletin 4401, 4 pp. Describes a-c magnetic contactors, 2-, 3-, and 4-pole, designed for continuous duty operation, 2- or 3-wire control. They are applicable for starting motors directly across the line, for disconnect purposes in conjunction with suitable auxiliary switches, and for special control panels. Ward Leonard Electric Co., Mt. Vernon, N. Y.